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Recent development of planar microwave sensor for material characterization of solid, liquid, and powder: a review

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ABSTRACT

Microwave is the most popular sensor in industrial applications for detecting material characterization. Over the past decade, microwave sensor is high demand, especially in medical for detecting cancer in the human body, agriculture for detecting moisture of soil, and freshness in the food industry. The previous study has shown that the high demands of the microwave sensor in industrial applications make researchers always think of new ideas to design microwave sensors to improves accuracy and sensitivity. This paper reviews an investigation of material characterization of recent developments of a planar sensor for various contaminants and parameter value of solid, liquid, and powder as material under test (MUT). Planar resonator sensor enhances the weakness of conventional sensors in bulky size, required a large volume of samples, and high cost. This planar sensor will differentiate MUT properties based on scattering parameters at various operating frequencies. The framework presented in this review paper includes new developments in resonator structure as well as advanced design of potential future research work. Previous studies will be objectively analysed and compared in order to gain a better understanding of microwave resonant sensors and to develop innovative concepts to further enhance application research involving material characterization.

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1. INTRODUCTION

Material characterization at microwave frequencies has a long tradition since the early 1950s [1]. Industrial growth currently necessitates accurate material characterization that is cost-effective, highly accurate, and compact, which plays an important role in identifying material characteristics in medical, agriculture, food industry, oil and gas, wireless, ultra-wideband (UWB), and millimeter-wave applications [1]-[6]. Therefore, it is necessary to consider frequency testing and the type of material to be tested as well as the frequency before selecting the appropriate dielectric measurement technique.

In general, it is also included the microwave method for characterizing material which is a resonant method, and non-resonant methods [7], [8]. Non-resonant approaches are frequently used over a frequency range for electromagnetic properties, whereas resonant approaches are typically used to correctly understand a single frequency or several distinct frequencies of dielectric properties [1], [9]. Stripline, coplanar waveguide, and microstrip are three types of planar transmission lines that are frequently used in microwave sensors. Stripline is a modification of coaxial lines and two wirelines that is widely used over a wide frequency range because it lacks a low-frequency cut-off, whereas the top surface of a microstrip has an open conductor pattern and a line geometry with a single ground plane [10]. The coplanar waveguide is made up of two parallel ground plane sections and a central strip width [11].

In recent years, various techniques for characterising the dielectric properties of the material have been developed [12]-[14]. Thus, cavity waveguide perturbation [15], [16], free-space transmission [17]–[19], open-ended coaxial probe [20], [21], and planar transmission line technique [22] have been used to characterise materials in a variety of applications. Dielectric measurement is affected by several factors, including frequency, temperature, material type, sample size or thickness, costing, contact or non-contact, and destructive or non-destructive [23], [24].

Material characterization has traditionally been accomplished with high sensitivity and accuracy using conventional waveguide, dielectric, and coaxial resonators [25]. The traditional resonator sensor, on the other hand, is typically massive, costly to manufacture, and requires a significant amount to detect the sample of material under test (MUT) [25], [26]. Planar resonant techniques have become among the most popular techniques in recent years due to their advantages of compact size, low cost, and ease of manufacture [27], [28]. This technique, however, produces low sensitivity and Q-factor values, limiting the range of material characterization [29], [30].

2. RECENT DEVELOPMENTS

In recent years, microwave sensors for characterization of dielectric materials have been widely used in a wide range of applications in solid, liquid, and powder samples. Thus, the microwave planar sensor fulfills the requirements in industrial applications [30], [31]. The previous study design of planar sensor for material characterization of solid, liquid, and powder material has been described in terms of operating frequency, the type of sample used, and the observed results. Thus, a comparison of applications of the recent development of planar sensors is tabulated on a table.

2.1. Solid material

To enhance accuracy and sensitivity of the sensor, previous study has investigated the design of the sensor for a solid sample of material characterization. According to Subbaraj *et al.* [32], the designation of the transmission line has been connected to electromagnetic band gap (EBG) cells and operates at 2 Ghz. This sensor measures the dielectric materials' complex permittivity. For high-loss and low-loss materials, the sensor tested Teflon, acrylic, neoprene, polypropylene, polyurethane, and PVC samples. R-squares yielded an excellent result of 96.67 percent for the imaginary part of permittivity and 99.83 percent for the real part of permittivity. However, this sensor design of EBG cells was complex and complicated which affect the effectiveness of the sensing area.

Alahnomi *et al.* [33], research on the asymmetrical split ring resonator safety, security, and rescue robotics (SSRR). These sensors operate at 2.3 GHz to reduce insertion loss and achieve a high Q-factor of 407.34 with less insertion loss. Meanwhile, the Q-factor of the quasi-linear pattern is 278.78. As a sample for the sensor, they used an overlay of fresh meat. The asymmetrical split ring resonator sensor is easy to construct, cheap, and simple to simulate, and it can be used to improve the accuracy of a microwave sensor.

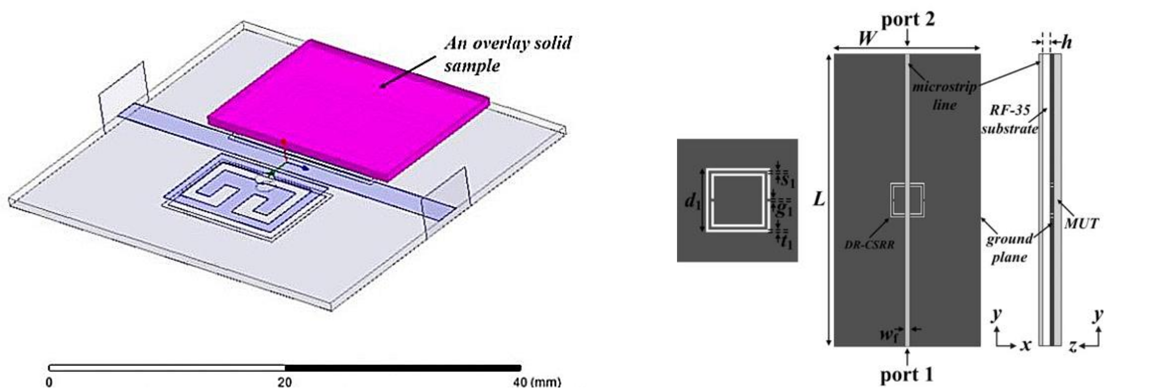
Meanwhile, Then *et al.* [34] demonstrated a lumped element model on a modified microstrip ring resonator sensor operating at frequencies ranging from 0.5 to 4.5 GHz, with a resonance frequency of 3.2 GHz. This sensor measures dielectric predictions as well as the moisture content of peat and sand soil samples. Also, Alahnomi *et al.* [35] the perturbation theory is applied to the development of a new symmetrical split ring resonator with spurlines filters that influence the Q-factor and resonance frequency. At 2.22 GHz, this sensor achieved narrow resonance, low insertion loss, high sensitivity, and a Q-factor of 652. The samples Roger 5880, Roger 4350, and FR4 were used to validate the sensor's sensitivity for detecting material characterization. The results of the average percentage of accuracy show that this sensor 97-98% compared to other sensors.

In another study, Rahman *et al.* [36] presented a new dual-band complementary folded arm (CFA) split-ring resonator sensor. It is operated at 2.5 GHz for solid and 3.9 GHz for liquids. The advantage of this sensor which can characterize both solid and liquid dielectric properties. The sample that used is Teflon, Roger 5880 and Roger 4350 for the solid sample while chloroform and hexane for liquid sample. An overlay solid sample is shown in Figure 1(a).

Yeo and Lee [37] created a high-sensitivity microwave sensor for dielectric characterization of planar materials in a microstrip transmission line using an interdigital-capacitor-shaped defected ground structure. The sensor was created by modifying the straight ridge structure of an H-shaped aperture, as shown in Figure 1(b). This sensor was tested at 1.5 GHz against conventional sensors based on a double-ring complementary split-ring resonator (CSRR), a single-ring CSRR, and a rotated single-ring CSRR. When compared to the double-ring CSRR-based sensor, this sensor was two times higher for a low permittivity of 2.17 and 1.42 times higher for a high permittivity of 10.2.

Therefore, another study of Alahnomi *et al.* [38] introduced a T-resonator for solid sensing applications. This sensor-operated frequency at 2.4 GHz under unloaded sample. The solid sample that used for sensing is FR4, Roger 5880 and Roger 4350 with different permittivity. This sensor has a narrower bandwidth and a high-Q factor with high sensitivity, according to the results.

Overall, by going through the previous research design which an array design of the patch sensor allows deposition of solid samples and leads to the sensor with a high level of sensitivity [39]. Thus, when the sensitivity of the sensor increases the Q-factor will be increased, which makes the sensor more reliable for material characterization in the future. Sensor improvements in Q-factor, accuracy, and compactness size make the sensor suitable for solid sample detection.



(a) (b)

Figure 1. Sensor design (a) dual-band complementary folded arm (CFA) [36] and (b) IDCS-DGS sensor [37]

2.2. Liquid material

Another major investigation for microwave sensors on the liquid material characterization by Kulkarni and Joshi [40], introduced a shielded vertically stacked ring resonator (VSRR) for low-loss liquid sensing permittivity variation. This sensor operates at a frequency of 2.45 GHz with a design of sensor consist of fed patch for the fill of liquid sample and shielded structure or box for parasitic to fill the liquid sample. This sensor has >100 Q factor that makes this sensor suitable for sensing samples of material. Thus, petroleum liquids that have been used for tested are N-Hexen, Petrol, and Diesel.

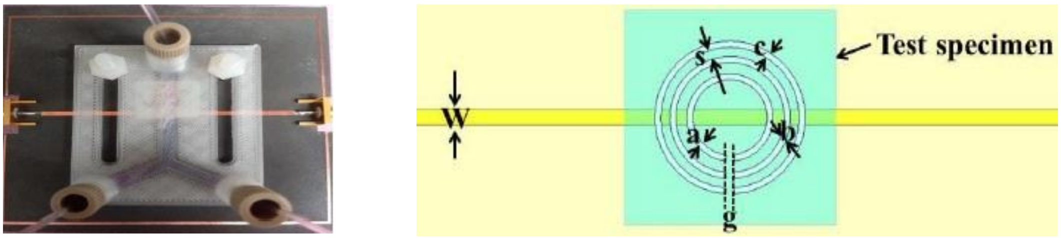
Thus, by Tiwari *et al.* [41] for liquid testing, a novel multi-band compact planar sensor with ISM (1.8 GHz, 2.45 GHz) and Wi-Fi (3.5 GHz) frequency ranges has been introduced. The sensor's objective was to achieve a simple design of a triple-band sensor with the same orientation of the triple rings as shown in Figure 2(a). Coconut oil, eucalyptus oil, mineral, and mustard oil are several samples of the liquid used for testing.

Another study by Wiltshire and Zarifi [42] as shown in Figure 2(b), Bi introduced a novel sensor for liquid sensing applications based on a planar sensor embedded with a 3D printed fluid channel. This sensor operated between 5.3 and 5.8 GHz and was embedded within a fluidic channel, allowing for a 50-μm proximity between the sensor and the liquid material within the channel. Methanol, IPA, ethanol, and reverse osmosis (RO) water were used as testing liquids.

Besides, Kiani *et al.* [43] created a microwave sensor that uses a split ring resonator to detect the dielectric constant of a liquid sample. The structure's sensor is made up of ring resonators with non-identical double splits that are located on the inside of power divider branches that operate at frequencies of 5.76 GHz and 7.85 GHz. This sensor measures the permittivity of various samples such as ethanol, methanol, glucose solution, and deionized water.

Acevedo-Osorio *et al.* [44] created a small resonant sensor with two bands that uses a single stepped-impedance-resonator as the sensing element. At the 2.45 GHz and 5.8 GHz ISM bands, it operated in differential and common modes. The liquid sample was tested with a single sensing region without sample location duplicated. Several samples with varying permittivity were tested.

By going through all of the designs, an array design of the patch sensor allows for MUT deposition and results in high sensor sensitivity [39]. As a result, the sensor's simple design makes it easier to demonstrate using software and hardware. The microwave sensor is small and compact, it is therefore ideal for the lab-on-a-chip approach and the evaluation of material properties.



(a) (b)

Figure 2. Sensor design (a) ring structure in the 3-D printed channel and (b) multiband sensor

2.3. Powder material

A recent study has investigated several designs of the sensor to enhance the sensitivity and accuracy of powder samples for material characterization. You and Mun [45] a planar ring sensor for low-loss powder dielectric measurements was introduced as shown in Figure 3(a). The measured reflection coefficient was converted to the relative dielectric constant using a lumped-element model. At room temperature, this sensor operated on a frequency range of 1 GHz to 3 GHz. Soy, barley, wheat, and rice powder are several samples of powder used for material characterization. The percentage error of this device is below 3% make this sensor suitable for material characterization.

Another design by Coutinho *et al.* [46], design a microwave planar sensor with four poles of coupled resonators for characterization of powdered foods as shown in Figure 3(b). This sensor operated at frequencies ranging from 1.0 GHz to 3 GHz. This sensor estimates the permittivity of six different types of grains. As examples, two types of oatmeal, three types of corn, and wheat flour are used. The calculated permittivity values show that the preliminary data can be used for further investigation due to experimental sensitivity is 36 MHz/Fm^{-1}.

(a) (b)

Figure 3. Sensor design (a) ring sensor [28] and (b) four coupled resonators [29]

3. SUMMARY OF RECENT DEVELOPMENTS PLANAR SENSOR

Table 1 compares the sensitivity and accuracy of the planar sensors of previous research findings. The comparison includes Q-factor value, sensing materials, resonant frequency, and advantages of the planar sensor. Planar techniques have the advantage of compactness of design with ease of fabrication. However, due to their low Q-factor and sensitivity, these techniques are limited in their ability to detect small changes in the dielectric properties of materials [47], [48]. It can be seen that the recent design has a Q-factor value which is >100. Thus, all elements of materials have a high Q-factor value due to the size and concentration of materials occupied in the sensing area make it more concentrations of electric fields interact with dielectric materials of samples. As a result, the most recent design has a percentage error of less than 5%, increasing the sensor's sensitivity and reliability. The sensor's Q-factor and sensitivity are also affected by the narrower bandwidth.

Table 1. Comparison recent developments planar sensor

Ref/Year	Q-factor	Sensing	f_o/GHz	Advantages
[32]/ 2016	280	Solid	2.4	Extend the interaction transmission line's time duration with the MUT Quick calibration and simplicity Appropriate for both low-loss and high-loss materials
[33]/ 2016	407.34	Solid	2.2	The reflected signals' very narrow bandwidth raises the Q-factor Suitable for dielectric low loss material with a volumetric moisture content Other types of filters can benefit from harmonic suppression.
[34]/ 2016	345	Solid	3.2	With a margin of error of less than 5%, it is accurate Calculate the dielectric constant for various soil types A simple and direct design with a narrower bandwidth
[35]/ 2017	652	Solid	2.22	A small resonance with a low insertion loss High-Q and sensitivity that reached 652 With a margin of error of only 1.3 percent Manufacturing is simple and inexpensive
[36]/ 2018	446, 506	Solid	2.5 and 3.9	Operate two different materials at two different frequencies High Q-factor of 446 and 506 for solid and liquid sample respectively An array design enables sample deposition, resulting in high sensitivity
[37]/ 2019	458	Solid	1.5	Simple design with improved sensitivity and accuracy Suitable for sensing solids, microfluidic liquids, and biological samples wirelessly Suitable for chip less radio frequency identification (RFID) sensors' environmental sensing unit
[38]/ 2020	662	Solid	2.4	Simple design and easy to fabricate Require a small amount of sample to be tested Narrower bandwidths increase quality factor value
[40]/ 2015	265	Liquid	2.45	Simple designs with shielded structures or boxes for placing liquid samples make measurement simple The accuracy percentage is less than 2%
[41]/ 2018	398	Liquid	ISM band (1.8, 2.45) Wi-Fi band (3.5)	Simple design and easy to fabricate Capability of multiband dielectric sensing Suitable for all kind of oil specimens
[42]/ 2019	425	Liquid	5.3 and 5.8	Various materials are used depending on the application More flexible and cost-effective sensing Improving the device's minimum detectable concentration to 0.1% ethanol: water
[43]/ 2020	280, 160	Liquid	5.76 and 7.85	Permittivity of a single test sample measured in two frequency bands Simple design and easy to fabricate Can be used for further investigation industrial and medical fields due to sensitivity of the sensor is 0.28 and 0.3: measure glucose concentration in biological materials (blood, eye tears, and saliva mouth)
[44]/ 2020	111.56, 21.39	Liquid	2.45 and 5.8	Portable and simple design Require single sensing region for two bands without duplication of sample Sensitivity of the sensor is 1.11MHz/Fm^{-1} and 2.35MHz/Fm^{-1} which suitable for further analysis of a liquid and solid sample
[45]/ 2012	286.5	Powder	1 to 3	Simple design and easy to manufacture Portable and small in size Sensing is large for deposited sample Can be used for further investigation which percentage error below 3%
[46]/ 2018	385.6	Powder	1.0–3	Simple design and easy to manufacture Wider sensitive area suitable for more homogenously sample High sensitivity of 36MHz/Fm^{-1}

4. CONCLUSION

This article attempted to review and address some advanced planar sensor design technologies for a variety of materials-related applications such as medical, food safety, agriculture, bio-sensing, chemical materials, and quality control. A comparison of various designs of a planar microwave sensor for characterizing dielectric materials for solid, liquid, and powder samples using permittivity, resonance frequency, and Q-factor. The summary of sensor design, applications, and materials used as MUT has been highlighted, as well as comparisons between the various sensor designs presented. The emphasis was on each design's efficiency in order to achieve the highest sensitivity and precision for better measurement. This study was taken from a presented paper for each detail and measurement results from the particular design of the sensor. The previous sensors used various amounts of samples to detect material characterization of the samples. Different types of samples show different material characterization such as in terms of frequency resonate, permittivity, accuracy, compact in size, and high Q-factor. As a result, a planar sensor is suitable for the material characterization of solid, liquid, and powder. However, this planar sensor suffers from a low Q-factor. Due to this, there are several designs of the previous studies to overcome the weakness of these planar sensors. The sensor's size and the coupling gap between the ring resonator and feedlines are important because they affect the concentration of the electric field and the sensor's sensitivity. Further, planar resonator sensor can be easily integrated with other devices, low cost, and need a small size of MUT. Thus, design of planar sensor is simple, ease to fabricate, easy to generate with software, and compact in size of the sensor. In the future, the planar sensor could be used in a variety of applications, including cancer detection in human cell tissue (which also involves dielectric measurement) and monitoring the reading via the global system for mobile communications (GSM).

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