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Planar Microwave Sensors for Accurate Measurement of Material Characterization: A Review

Norhanani Abd Rahman*[1], Zahriladha Zakaria[2], Rosemizi Abd Rahim[3], Yosza Dasril[4], Amyrul Azuan Mohd Bahar[5]
[1]Department of Electrical Engineering, Politeknik Seberang Perai (PSP), Pulau Pinang, Malaysia
[1,2,4,5]Centre for Telecommunication Research & Innovation, Faculty of Electronics and Computer Engineering, Universiti Teknikal Malaysia Melaka (UTeM), 76100 Durian Tunggal, Melaka, Malaysia
[2]School of Computer and Communication Engineering, University Malaysia Perlis (UniMAP), Perlis, Malaysia
Corresponding author, e-mail: norhanani80@gmail.com*[1], zahriladha@utem.edu.my[2]

Abstract

Microwave sensor is used in various industrial applications and requires highly accurate measurements for material properties. Conventionally, cavity waveguide perturbation, free-space transmission, open-ended coaxial probe, and planar transmission line technique have been used for characterizing materials. However, these planar transmission lines are often large and expensive to build, further restricting their use in many important applications. Thus, this technique is cost effective, easy to manufacture and due to its compact size, it has the potential to produce sensitivity and a high Q-factor for various materials. This paper reviews the common characteristics of planar transmission line and discusses numerous studies about several designs of the microstrip resonator to improve the sensor performance in terms of the sensitivity and accuracy. This technique enables its use for several industrial applications such as agriculture and quality control. It is believed that previous studies would lead to a promising solution of characterizing materials with high sensitivity, particularly in determining a high Q-factor resonator sensor.

Keywords: *Material characterization*, *Planar transmission line, Microstrip*

1. Introduction

The development of the characterization of material properties at microwave frequencies started as early as the 1950s. This was when the great idea behind new measurement methods and techniques had formed. Several techniques were designed to characterize the dielectric properties of materials in [1-5]. Rapid industrial development currently requires a precise measurement of material characterization that meets the characteristics-being cost effective, highly accurate, compact, and that it is especially used t assess the quality and to identify characteristics of the materials in the food industry, agriculture and bio sensing. The originality and freshness of the content in food are very important. The food industry requires accurate measurement methods which are fast to meet user requirements. In the world of agriculture, the determination of bulk density and moisture in the soil composition or structure of the seed can help improve the quality of agriculture. This is true, in line with previous studies that examined the content of moisture in the food and agriculture through the dielectric properties [6-9]. The investigative works on dielectric properties conducted within the field of bio-sensing to determine the properties of cells and tissues in human have been proposed by [10] and moreover, researchers [11, 12] find out the permittivity of the glucose solution based on changes in the glucose concentration. To meet the needs of these applications, the researchers have produced a variety of techniques appropriate to the specific material based on a set of frequencies to determine the dielectric constant of the complex permittivity. There are many techniques that have been designed and categorized and they include the non-resonator and resonator methods [13, 14].

The non-resonant methods, over the frequency range can be used to determine the electromagnetic properties [15], while this method gives a more accurate knowledge of dielectric properties over a limited frequency range or a single frequency. The resonant method such as

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the cavity perturbation technique accomplishes the dielectric measurement with a higher degree of accuracy [16] and can provide better sensitivity as compared to the broadband methods. The preferred measurement technique is based on several factors such as frequency range, permeability and permittivity, homogeneous or isotropic, the form of material, sample size restrictions, destructive or nondestructive and cost. Based on the criteria, cavity waveguide perturbation [17, 18], free-space transmission [19-21] open-ended coaxial probe [22-24], and planar transmission line technique [25, 26] have been used for different applications for determining the material characterization. In the cavity waveguide technique, the sample size was limited by the sensor design. This method will affect the material under test (MUT) in terms of the sensitivity of the sample [27]. On the other hand, the free-space transmission technique does not require any special sample preparation but it is suitable for materials under high temperature and suitable for inhomogeneous dielectrics.

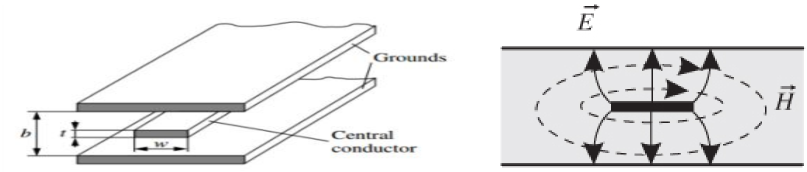
However, it is difficult to get accurate readings using this technique because the distance and position of the horn lens antenna may tend to affect the focusing ability [28]. For open-ended coaxial sensor designs, it is suited for measurements on liquids and semi-solid except for determining the permittivity of pulverized and granular samples because there will be air gaps or air bubbles between the end of the sensor and the sample [7]. In order to get a simple sample preparation, with the accuracy of resonant cavity methods in extracting local material properties, and to make it easily integrate with other microwaves [29], the planar transmission line is the best technique compared to other techniques. Therefore, these paper studies the recent development for the planar transmission line technique with several designs based on the methods, frequencies, techniques and technologies used in order to produce a highly accurate and sensitive sensor.

2. Planar Transmission Line

Planar transmission lines have been used comprehensively in the previous literature to determine the electromagnetic properties of materials, including substrate, sheet and thin film samples. There are many advantages of using it, such as ease of fabrication, compactness, low cost and easy handling. It is also used in antenna applications [30, 31]. In the material measurement, three types of planar transmission lines often used are the stripline, coplanar waveguide and microstrip. Planar circuit methods can be categorized into broadband and resonant methods. The most commonly used is resonant methods because of their higher accuracy and sensitivity. In planar resonator methods, the MUT is placed either on the top of the resonator or inside the substrate depending on the maximum electric field location (E-Field). This method has the advantage of having compact size, which is easy to manufacture and which cost is low. Conversely, these techniques produced a low quality factor (Q-factor) and poor sensitivity which decrease and limit the use of different materials [32, 33]. Therefore, a novel structure of planar microwave sensors for determining and detecting the dielectric properties in common solid, sheet, liquid or semi-solid to produce high Q-factor [34] with the capability to suppress the undesired harmonic spurious, has been established by several researchers.

2.1. Stripline

The stripline structure is actually yielded by the modification of the coaxial lines and two wire lines. It consists of upper and down grounding plates, a strip conductor centered with two equal slabs of a dielectric, ferrite, or semiconductor as shown in Figure 1. For the characterization of the material properties, in a stripline structure the sample being tested can be placed below or above the center strip through the open sides. The stripline structure of a two-conductor line has no low frequency cut-off, so it can be applied over a very broad frequency range [35]. The stripline also has an advantage in the low attenuation losses and a good electromagnetic protecting potential for high-quality factor and low-interference applications. Most of the stripline circuits are small, and they are a pure TEM mode propagation. However, the problem with stripline is that the design is seen as complicated because the conductor is placed at the middle between the ground plates, so the air gaps between the conductor may cause perturbation to the impedance [36]. It is also not suitable to measure the dielectric loss of the higher-permittivity low-loss materials due to the energy scatter by the specimen under test for optimal cavity perturbation [37]. The striplines also require a strong symmetry and it is difficult to develop a circuit because it requires the elimination of the symmetry to access the center conductor [38]. However, the structure of stripline does not match the bias circuit and integrated chip if some changes were made to the circuit configurations. The stripline, is hence, expensive to fabricate than the microstrip.

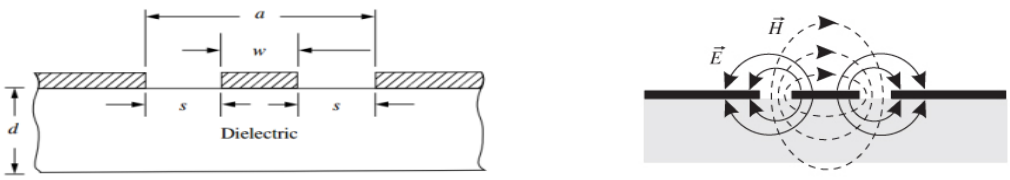


(a) (b)

Figure 1. Stripline Structure (a) Geometry (b) TEM Field

2.2. Coplanar Waveguide (CPW)

A CPW structure has two ground plane-parallel sections and strip width located in the middle as shown in Figure 2. The ground planes and center conductor are placed at the same level with the substrate surface. CPW has a small gap, and it can support electric fields focus on the dielectric [39]. Besides that, the low dispersion of CPW caused by a little fringing field in the air space and the wave propagation mode CPW is quasi-TEM [40]. Coplanar technology supports the possibility to design highly concentrated microwave integrated circuits, especially if additional use is made out of a lumped-element technique. The layout of the circuit, which is very small, can be made up to the highest frequencies. Unlike slotline, CPW is compatible with non-reciprocal ferrite devices as the magnetic field is elliptically polarized. The structures of the CPW mode are supported by the parasitic mode and coplanar slotline mode. To increase the insertion loss, the air bridges between ground planes are required to restrain the unwanted slotline mode. However, this will increase the fabrication cost. Besides that, CPW also has a poor Q-factor and additionally, the heat sinking capabilities are low [36]. Consequently, the thick substrates are required and the concentration of its current will occur within the metal edges that produce a higher ohmic loss [41].



(a) (b)

Figure 2. CPW Structure (a) Geometry (b) TEM Field

2.3. Microstrip

The microstrip line is the transmission line geometry with a single ground plane and the conductor pattern on the top surface being open, as shown in Figure 3. Microstrip line is an open structure, so it has an extensive fabrication advantage over the stripline. It also features attractive criteria such as ease of adjustment and enhancement. The electromagnetic fields exist partly within the substrate and the air above the dielectric substrate of the microstrip line. The propagation of electromagnetic waves in the microstrip is not original TEM due to the combination of a dielectric medium and an open air space. Thus, it is usually assumed that the electromagnetic field in the microstrip line is quasi-TEM [42]. Microstrip is the first choices in the microwave device caused by excess physical characteristics of compact size, integration with solid-state devices, simple fabrication, good heat sink and a decent mechanical support [8]. It is also extensively used in the characterization of the electromagnetic properties of materials, notably thin films [43, 44] and substrate materials. However, the microstrip supports the Q factor of about 80 and it is difficult to mount the chip in the shunt mode [45]. Table 1 shows the advantages and drawbacks between the transmision line that is used in determining the material characterization. The microstrip line most widely used throughout the research is based upon the advantages available to it. However, the design that uses a microstrip line is focused on the sensitivity to obtain high Q-factor.

(a) (b)

Figure 3. Microstrip Structure (a) Geometry, (b) TEM Field

Table 1. Comparison of Transmisson Lines

Transmission Line	Advantages	Drawbacks
Stripline	Large impedance range High Q- factor Low radiation No dispersion Moderate Cost	Difficult mounting of elements Limited impedance range Limited frequency band
Coplanar Waveguide	Large impedance range Low dispersion Easy mounting of series and shunt elements Wide frequency range Low cost	Low Q-factor Medium radiation
Microstrip	Simple integration Easy mounting of series elements Wide frequency band Low cost	Low Q-factor

3. Recent Development on Planar Microwave Sensor for Material Characterization.

Most studies conducted on the planar transmission line, are more focused on the use of the Microtrip resonator [44-46] as a simple, cost effective structure fabrication, where it can be used for solid or liquid measurement and it is easy for sample preparation. Based on these criteria, the recent development of the microstrip resonator will be explained, with regard to the use of the liquid, solid and the mixture of material samples.

3.1. Liquid Material

Previous studies have investigated a design of sensor to enhance the sensitivity and accuracy on the liquid sample for the material's characterization. There are a number of microstrip resonator designs such as [49] where it designed a microfluidic sensor based on a high Q- factor. The sensor is a combination of a single split ring resonator (SRR), proximity-coupled with a microstrip transmission line. The SRR is made through the metal loop with a square shape and split on the side operating on 1.9 GHz, showing that the water content in the 50% sample mixture of ethanol-water and methanol-water affects the permittivity. This method is proper for the classification, identification and characterization of biochemical and chemical analytes. Researcher(s) in [50], designed a dielectric resonator with a split ring resonator (DR-SRR) methods for liquid sensor, that gives more improvement to the quality factors in the range of 330 compared to the single ring resonator. Split ring Resonator (SRR) and DR-SRR are proven on saline solutions and water. Notably, this method is suitable for higher frequencies that range between 20-40GHz because the lost tangent of water is very high. The reservoir placed above the sensor as can be seen in Figure 4 can well improve the Q- factor and the accuracy of the measurements. Another design [51] with a Complementary Split Ring Resonator (CSRR) produced a powerful electric field in a small area as $2x10^{-5}\ \lambda_0{}^2$ and high sensitivity of dielectric property surrounding the materials. The device that operates at around 2GHz has a low-cost and compact structure. CSRR is supported by the polydimethylsiloxane (PDMS) channel to deliver the binary mixture of water-ethanol. According to [52], the comparison of three microstrip resonator sensors between the ring, meander and minkowski fractal structures is drawn to determine the dielectric constant of palm oil liquid. The result shows that minkowski has high performance of the shift in the resonant frequency of 922MHz and insertion loss ε_r = 2.7 compared to the ring and meander resonators. Indeed, the minkowski has been potential for liquid and solid measurements.

In the research of [53], the authors introduce a novel design of a shielded vertically stacked ring resonator (VSRR). They use the shielded VSRR for the parasitic ring patch that acts as a ground plane and use a layer of the low-loss liquid to fill the limited space between the fed path and parasitic patch. The VSRR sensor can be used for low-loss petroleum liquid where it can be easily poured into the stacked box. Deshmukh and Ghongade [54] introduced a simple ring resonator as a sensor with the gap 0.2mm and simulated in HFSS software. The microstrip ring resonator (MRR) is approved using the Vector Network Analyzer which non-invasively measures the blood glucose concentration in human beings. The analyzed MRR showed a good insertion loss that occurs in -8.26dB on the frequency of 1GHz. The sample of aqueous glucose solution is placed above the microstrip ring resonator. Another approach has been developed by [55], whose design is based on multiple split ring resonator (MSRR) with high performance of quality factor 525. The sensor with the glass capillary tube as shown in Figure 5 is analyzed to show the correlation between relative permittivity and dielectric properties and the result of complex permittivity gives less than 0.5%. The method is operating at frequency 2.0GHz and 2.1 GHz with several solvents of water, ethanol, methanol using a quartz micro capillary. This method was improved from the enhanced coupling peripheral ring resonator [56]. The summary of the recent development of the microstrip resonator for liquid measurement is shown in Table 2.

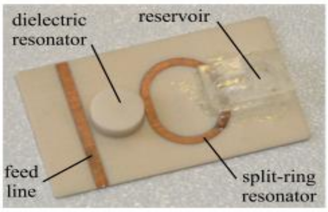


Figure 4. DR-SRR sensor [50]

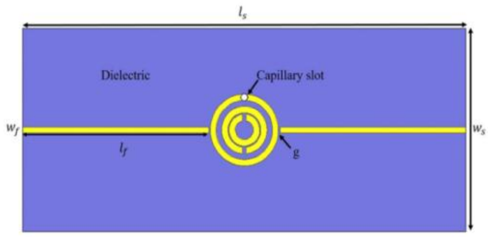


Figure 5. The geometrical diagram of MSRR [55]

Table 2. Recent Development Of Microstrip Resonator For Liquid Measurement

Ref /Year	Sensing Element	Application	Sample
[49]/ 2013	Split ring resonator (SRR)	Microfluidic sensor for high Q-factor	Ethanol-water and methanol-water
[50]/ 2014	Dielectric resonator - split ring resonator (DR-SRR)	Improves the Q-factor and accuracy of the sensor for material characteristics.	Water and saline solutions.
[51]/ 2014	Complementary split ring resonator (CSRR)	High-sensitivity sensor for microfluidic	Water-ethanol
[52]/ 2014	Planar microstrip	Comparison of three resonator sensors (ring, meander and minkowski fractal) for dielectric constant of a liquid	Palm oil
[53]/ 2015	Vertically stacked ring resonator (VSSR)	Improves the Q- factor and complex permittivity sensor for petroleum oils	Petroleum (N-Hexen, Petrol, Diesel)
[54]/ 2016	Microstrip ring resonator (MRR)	Microwave sensor for measuring blood glucose concentration in human being non-invasively	Aqueous glucose solution
[55]/ 2017	Multiple split ring resonator (MSRR)	Fluidic sensor for high Q-factor	Water, Ethanol, Methanol

3.2. Solid Material

Basically, the characteristics of materials also include the fact that the material is solid. Recent works of microtrip resonator focus on solid introduced by references [57] and [58], in which they study the dielectric characterization of the fat content of chicken meat and the comparative method of the coupling scheme in the ring resonator [57] designs a microstrip ring resonator (MRR) at 1GHz using a substrate Roger RT/Duroid 5880 showing the fat content for the measurement without added-fat contents, for a minced- breast sample with 36% shift observed from the unloaded resonance frequency, followed by 30% shift for a minced-thigh sample. Meanwhile, [58] enhances the MRR to the coupling ring resonator, where it shows a significant change on the resonance frequency when tested at different moisture contents of meat. The authors develop one port of the microstrip ring resonator compared with the MRR and testing at different coupling gaps in the range of 150 µm to 250 µm. It shows more than 23% resonance-shift, from the larger gaps. In addition, to evaluate the moisture content more efficiently, the same design of MRR [59] is used to observe the size of overlay material independent effective permittivity of biological tissues.

Another study by Ansari et al. [60] proposed a novel microwave non-invasive planar sensor based on the complementary split ring resonator (CSRR). The sensor is also etched on the ground plane of a planar microstrip line. The authors choose a rectangular and circular cross-section for their sensor design and use the wood, rubber, polyethylene, plexiglas, PVC, and teflon as samples. They compare between the two methods and discover that the circular CSRR has achieved a high sensitivity when compared to the rectangular CSRR and that it operates at 1.7GHz to 2.7 GHz. According to author(s) [61], they designed a transmission line connected with EBG cells operate at 2GHz. These sensors are used to determine the complex permittivity dielectric material. The proposed method tests on several samples of teflon, acrylic, neoprene, polypropylene, polyurethane, PVC appropriate for high-loss and low-loss materials. An excellent result for R-square's shown 96.67% for the imaginary part of permittivity and 99.83% for the real part of permittivity. The authors, in [62] introduced the symmetrical split ring resonator (SSRR) to enhance the insertion loss of the microwave sensors. This technique operated at 2.3GHz and can produce a great value of the Q-factor of 407.34 with less insertion loss, meanwhile the quasi-linear pattern has achieved high Q-factor value of 278.78. Authors used the overlay fresh meat sample placed above the sensors as shown in Figure 6. SSRR is easy to fabricate and simulate, cost effective, simple and available to improve the accuracy of the sensor for material characteristics compared to existing techniques. A new microwave microstrip sensor has been introduced by [63] which depends on a modified microstrip ring resonator sensor with a lumped element model. The microstrip ring resonator sensor operated between 0.5 GHz and 4.5 GHz with the resonance at 3.2 GHz and dielectric prediction based on different moisture contents of peat and sand soil samples. They used a RT/Duriod 5880 and placed a sensor with an acrylic holder for the sample loading as shown in Figure 7. The summary of the recent development of the microstrip resonator for solid measurement is shown in Table 3.

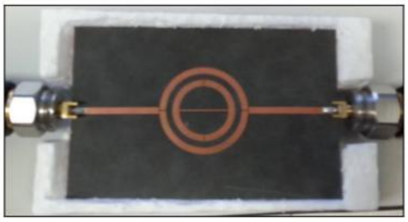


Figure 6. SSRR sensor [62]

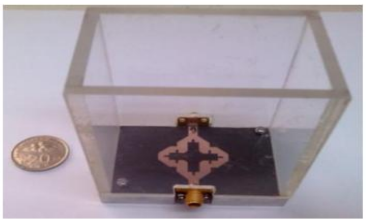


Figure 7. Sensor with acrylic holder for sample loading [63]

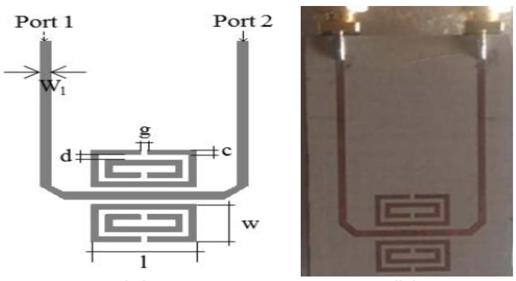
Table 3. Recent Development of Microstrip Resonator for Solid Measurement

Ref /Year	Sensing Element	Application	Sample
[57]/ 2013	Microstrip ring resonator (MRR)	Fat content of chicken meat based on dielectric properties	Meat breast chicken (fat content)
[58]/ 2014	Couple ring resonator	Increase the sensitivity of a resonator for different moisture contents	Poultry meat quality (different moisture)
[60]/ 2015	Complementary split ring resonator (CSRR)	Non-invasive measurement of complex permittivity	Wood, rubber, polyethylene, plexiglas, PVC, and teflon
[61]/ 2016	Transmission line coupled with electromagnetic band gap (EBG)	Electromagnetic non-destructive material characterization of dielectrics	Teflon, Acrylic, Polypropylene, Polyurethane, PVC, Neoprene
[62]/ 2016	Symmetrical split ring resonator (SSRR)	Produced high quality factor for characterizing solid materials.	Overlay fresh meat sample
[63]/ 2016	Modified microstrip ring resonator sensor with lumped element modeling	Soil moisture and dielectric predictions measurement	Peat and sand soils

3.3. Mixture Sample

Usually, the choice of techniques depends on the required measurement accuracy, the frequency of interest, the expected value of permittivity (*εr*), material properties or material forms such as, powder, liquid, sheet, or solid. Indeed, this paper shows the studies using the planar transmission line using the material form for the mixture samples. The authors [64] propose a circular patch resonator for measuring the microwave dielectric constants and loss tangents of nematic liquid crystals (BL006). This technique operates over the frequency range of 4.8–8.7 GHz. Meanwhile, [65] designed a coupled ring resonator of dielectric characterization of a closed ring resonator (CRR) and split ring resonator (SRR) for three lengths such as λ , λ /2, and λ /4 with the coupling gap of 0/41mm. Authors used two types of samples, semi-liquid form for the bio sample and powder form for the ferromagnetic. Results showed the parameter's dielectric measurement using CRR device to be more accurate than by using the SRR.

The authors, in [13] introduced a microwave technique dependent on complementary split-ring resonators (CSRRs). This technique was designed for dielectric characterization to meet the characteristics of materials such as air, Teflon, RO3003 and FR4. The sensor is working in the range of 0.8 GHz to 1.3 GHz band. The MUT was located above the ground plane through the microstrip line in order to create a stopband filter that can produce a perpendicular electric field to stimulate the sensor to change the resonant frequency. Based on Rusni et al, they designed a Multiple Split Ring Resonator operating at 5GHz. The first study by [66], differentiated the design of sensor-aligned and center-gap gap studied to get the high Q factor and the permittivity of some solid samples such as FR4, Duroid RT 5880 and Rexolite. It was also carried out by the second study [67] by using the same sensor that measured the permittivity of liquid samples such as rexolite, ethanol, methanol and water with good quality factor of 130. A new technique has been introduced by [68] using a Split Ring Resonator (SRR) to determine the relative permittivity characterization of liquid and solid, and determine the solid thickness of materials below 2 GHz. The structure as in Figure 10 consists of two SRRs hosted on a microstrip transmission line. The sensing principle is based on the detection of the notch introduced by the resonators in the transmission coefficient and suitable for the determination of the thickness of thin films between 100 µm and 1 mm. For the solid measurement, the sample was placed over the sensor, whereas another measurement sensor was immersed in the liquid sample. This technique also has the advantages of low-cost fabrication, low-complexity, the fact that it is fully submersible and reusable. The summary of the recent development of the microstrip resonator for the mixture samples measurement is shown in Table 4.



(a) (b)

Figure 10. (a) Sensor layout (b) Manufactured prototype [68]

Table 4. Recent Development of Microstrip Resonator for Mixture Samples Measurement.

Ref /Year	Sensing Element	Application	Sample
[64]/ 2011	Circular patch resonator	Measurement of microwave permittivity of nematic liquid crystal	Liquid-crystal
[65]/ 2012	Closed Ring Resonator (CRR) and split ring resonators (SRR)	Microwave characterization of dielectric materials	Spirulina platensis-gietler (semisolid) and ferrite (powder)
[13]/ 2012	Complementary split-ring resonators (CSRRs)	Material characterization	Air, Teflon, RO3003 and FR4
[66], [67]/2014	Multiple Split Ring Resonator	Material characterization	FR4, Duroid RT 5880, Rexolite, ethanol, methanol and water.
[68]/ 2016	Split Ring Resonator (SRR)	Sensor for thin-film detection and permittivity characterization	Foam, High density foam, Polyethylene, FR4, Oil (Paraffin, Olive, Peanut, Almond, Soy, Lemon, Castor), Chloroform, Acetone

4. Conclusion

This paper presents a planar microwave sensor in a variety of designs for the microstrip that meet the solid, liquid and mixture samples. There are various techniques for measuring dielectric properties to accommodate the industry requirements in the food production, agriculture, bio–sensing and quality control where they need a sensor that is easily handled, reasonably priced and highly accurate. The most popular method used is the planar microstrip which has been described by various studies. However, this method has a low Q-factor. Nevertheless, the studies that have been described to perform a variety of ways to obtain a high Q factor seek to determine the relative permittivity of the MUT and they are related to the resonant frequency. Elements that change the Q factor is the size of the coupling gap between the ring resonator and feed lines, where it affects the strength of coupling and the resonant frequency [69, 70]. Additionally, the Q-factor of a slot resonator can be increased by reducing the size of the sensor and achieving a high permittivity value with low loss material in a parallel plate capacitor [71]. Another way is by stacking the parasitic patch at a spacing of almost half a wavelength from the feed patch, which can produce a high Q-factor [72, 73]. The distance between the resonators forming the resonator patch leak will enhance the gain [74]. This current work is expected to provide ample knowledge about the recent development of the planar microstrip to determine the dielectric properties in the materials based on a specific design for a high sensitivity and accuracy of the sensor capable to detect a variety of materials such as solid, liquid or mixture.

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