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Current developments of material characterization using microwave resonator based sensors: a review

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Abstract- This paper presents an important review in development various types of resonant sensors technology used in previous years. Most of the resonators are designed for material characterization in specific applications area. In the last few years, several resonant sensors with different methods and techniques are compared in order to propose a new novelty in resonator designed. Most importantly, the new proposed structure must have high quality factor to gain improvement in an accuracy and sensitivity of the resonant sensor. This device will discriminate the composition and properties of samples based on scattering parameters. The previous studies will be reviewed and critically compared in order to gain better understanding in microwave resonant sensors and new ideas for further research improvement in application which required characterizing of materials.

1. Introduction

Precise measurement of material properties has gained significant importance over the last decade. The capability to non-destructively perceive exact properties of a material undertaking physical or chemical changes has led to many applications in industry, chemical and pharmaceuticals. In the food production, the interest in dielectric properties of agricultural and food materials has been principally for expecting heating rates when the materials are exposed to high frequency electric fields. Products from nature sources and many other agricultural products have been studied broadly. An important request of microwaves in the food industry has been the non-invasive determination of moisture content and its effect on the dielectric properties of materials. Microwave methods for dehydrating of food products have also been very prevalent [1].

Microwave sensors for the non-invasive classifications of biological and chemical materials have been developed lately. Resonant methods offer the expectation for highly accurate measurements at a single or discrete set of frequencies. Conventionally waveguide, dielectric, and coaxial cavity resonators have been used for characterizing materials purposed. Most of the methods and techniques applied are based on applications used by industries. A wide category concerns the dielectric properties of materials, for which microwave sensors are extensively employed working either as resonators or as transmission and reflection elements and some of it as absorption element. Wideband permittivity measurements are mostly made by transmission sensors or reflection sensors such as coaxial probes. However, this type of measurement is often too complicated for industrial applications [2]. So that, resonant sensors are take placed as current complex permittivity measurements.

Sensors needing simply scalar measurement allocate less expensive and more robust instrumentation to be employed; resonant sensors device can be fully defined in terms of scalar measurements, so that they afford themselves to use for industrial applications, whenever a wideband sensors characterization is not compulsory. A typical application of resonant sensors has been introduced in the previous research work [2]. In RF and microwave circuit design the dielectric permittivity of substrate plays a crucial role and requires accurate assessment over a broad band of frequencies. Knowledge of these properties plays an important role in the sensitive device of variety circuit technologies. The following sections purpose to provide an overall discussion of some well-established dielectric measurement methods, primarily applicable to moderate and high loss solvent samples and even for solid and gas samples [3].

Moreover, by presenting an accurate equivalent circuit exemplary for the planar resonator sensor the experimental calibration procedure is prevented. The cheaper and simply of constructing allows the use of the resonator also in disposable manner and an effort has been made to introduce recent method on solvents characterizing using planar resonant sensors industrialized by various researchers to fulfil the current demands of many applications especially biological and chemical industries. This paper introduces several designs with different frequencies, methods, techniques, and technologies. This information is expected to provide researchers with reference for developing future designs.

Characterization of Solid: Several studies have been conducted on solid samples for materials characterization in order to introduced novel resonant sensors design with improvement in accuracy and sensitivity of the device [1, 3, 4 and 8]. For example, Elisa Fratticcioli, Marco Dionigi, and Roberto Sorrentino, the authors produced microwave planar resonant sensor by implementation of scalar two port measurement method. There are similarities between both papers in term of frequency. The operating frequency is 500-800 MHz on 2004 and the first paper produced on 2002 used 656.58 MHz as operating frequency. The improvement in Q-factor, accuracy and robustness has been made. This method used is suitable for detection moisture content in wet powdered materials [1].

G. BiffiGentili, G Avitabile, M.Cerretelli, C.Riminesi, and N.Sottani were designed Cross-Shaped microstrip ring sensor with full planar microstrip technology. A scalar network analyzer is used to compute the resonant frequency and the matching amplitude of the transmission parameter for the fundamental mode. The complex permittivity is estimated by inverting the measured parameters using by an algorithm based on Artificial Neural Network (ANN). This design was modified based on their research work on 2001 "full-wave modelling of microwave planar reflection sensors of material moisture testing," The design structure has three layers of substrate with different dimension specifications. Upper and second layers are using RO4003 substrate and the bottom layer is using FR4 materials. Each layer has own function which is input, hidden and output port of the sensors. The sensor is very tough because it's multilayer structure and easily produced by less expensive printed circuit technology. The relative error of the system, are very small which is less than 3% based on tested result on several samples [4]. Table 1 shows that, the comparison previous research works in solid materials characterization due to different type of methods and techniques.

Table 1: Comparison Previous Research Works in Solid Materials Characterization.

No	Title/Author/year	Details/Remarks
1	A Planar Resonant Sensor for the Complex Permittivity Characterization of Materials. Elisa Fratticcioli, 2002	- Resonant Frequency : 656.58 MHz - Samples : Teflon, PVC, PEHD, Nylon - Reducing cost - Improving robustness - Excellent accuracy
2	A Simple and Low-Cost Measurement System for the Complex Permittivity Characterization of Materials. Elisa Fratticcioli, 2004	- Frequency 500-800 MHz - Reduce cost - Improves robustness - Suitable for measurement in compact areas. - Can be disposable
3	Microwave permittivity measurements through cross-shaped ring sensors. G. BiffiGentili, 2002	- Samples : Teflon, R4003, FR4, RF35 and glass - Extremely compact - Good accuracy - Higher sensor TM modes

Characterization of Liquid: The characterization of materials is not focused on solid phase only but all of phases are included liquids, gases and mixtures. Several studies on liquid materials characterization has been conducted and has been discussed on succeeding paragraphs [2, 6, 8, 9, 11 and 13]. For example, Nora Meyne designed a split-ring resonator by combining with dielectric resonator coupling for accuracy enhancement. This resonator was designed in simulation software before proceed to the fabrication procedure. The sensor is simulated using the 3D full-wave solver Ansys High-Frequency Structure Simulator (HFSS). The complex permittivity of water and saline solutions is tested using a first order Debye model. The advantage of this filter over the resonant sensor presented by Elisa Fratticcioli [1] which is the sensitivity much better due to high Q-factor.

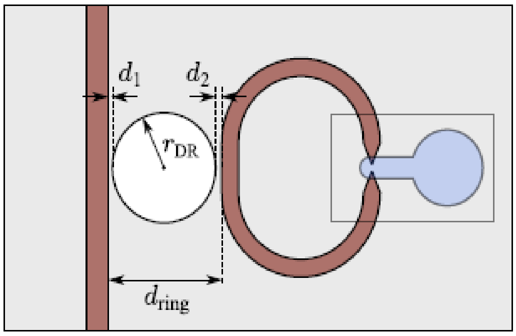

Fig 1: Geometrical parameters of the coupled DR-SRR sensor [2]

However, this design had limitation in bandwidth which is operated in 20-40 GHz frequency band. Moreover, the Q-factor is still relatively low for a DR resonator which is due to radiation. High performance resonant sensor could be produced using this method with some modification on its basic design. Other parameters study, such as bandwidth and frequency, also varied accordingly as expected [2].

Another example is integrated waveguide cavity resonator designed by Kashif Saeed was presented for Pharmaceutical industry application. The operating frequency of the sensor is 8 GHz and substrate material used in construction process is RT/Duroid with dielectric constant 2.2 and loss tangent 0.00009. The high-resonant fabrication is a transformation of well-known measurement cells where the dielectric constant is minimized by cavity perturbation from the change of resonant frequency and the factor. The advantages of the sensor are less costly and it can easily integrate with many other components. The error in the measured results is within plus minus 0.5% and this is prove that, the resonant sensor is much better in terms of sensitivity and accuracy [7].

Ali A. Abdul jabar, David J. Rowe, Adrian Porch, and David A. Barrow proposed a new technique for wide range applications by designing microwave microfluidic sensor by using microstrip split-ring resonator based on perturbation theory. The resonant frequency and Q-factor are depends on dielectric properties of resonator which is the operating frequency at 3 GHz. The design used Rogers Corporation RT/Duroid 5880 laminate substrate for fabrication process which is the permittivity is 2.2 and lost tangent 0.00009. It was modified from Kashif Saeed research work [7]. COMSOL Multiphysics software has been used to execute simulation on electromagnetic properties of the design. The resonator is compact and planar, making it suitable for a lab-on-a chip approach and suitable for evaluation of the materials properties [9].

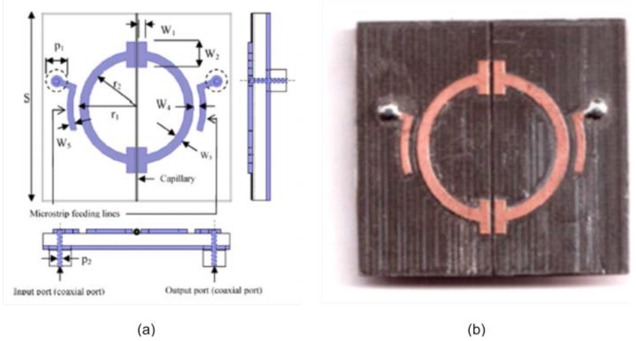

Fig 2: (a) Dimension of the DSSR and wide views of microwave coupling constructions. (b) Fabricated of the DSSR sensor [9].

Table 2: Comparison Previous Research Works in Liquid Materials Characterization.

No	Title/Author/year	Details/Remarks
1	Accuracy Enhancement of a Split-Ring Resonator Liquid Sensor Using Dielectric Resonator Coupling. Nora Meyne, 2014	- Frequency 20-40 GHz - Samples: water, saline solutions. - Improve Q-factor - Enhances accuracy of sensor
2	Substrate Integrated Waveguide Cavity Resonators for Complex Permittivity Characterization of Materials. Kashif Saeed, 2008	- Samples : Ethanediol, Acetone, Methanol and Dimethylsulphoxide - Frequency 8 GHz - Low cost - Integrated with many other components.
3	Microwave Sensor for Precise Permittivity Characterization of Liquids Used for Aqueous Glucose Detection in Medical Applications. U. Schwerthoeffer, 2014	- Resonant freq 2GHz - Samples : water-glucose -Very sensitive concentration less than 0.01% detectable. -Simple and highly sensitive sensor structure.
4	Novel Microwave Micro fluidic Sensor Using a Microstrip Split-Ring Resonator. Ali A. Abduljabar, 2014	-Samples: Hexane, chloroform, Ethanol, Methanol, water. -Frequency 3 GHz -Suitable for a lab-on-a chip approach. -Suitable for the evaluation of the materials properties.

Separation of samples into 2 classification phases which is solid and liquid are important for reviewing previous research works before proceed to designing stage. Different type of phases can leads to different technique to gain as high as possible the quality factor. The accuracy and sensitivity of the resonant sensors are depends on Q-factor at the same time improved the performance of the device.

Conclusion

This review paper has presented a thorough introduction into the various resonant methods and techniques for the materials characterization from previous to the latest journals, articles, conference papers, and thesis's. The advantages and disadvantages of the various techniques have been highlighted and have presented a thorough comparison. Discussion has been focused on performance of each technique to seek the best sensitivity and accuracy for better measurement and this paper has been supported through specific design sensors details and measurement results of each of the sensors. Apart from that, each resonant structure has pros and cons in terms of complexity, accuracy, cost and limitation of volumes detection samples. Different phase of samples will leads to different technique of design structure. However, some modification can be made to construct resonant sensors capability for measured more than one type of phase samples in a same structure.

The result of previous studies has been compared to seek the best performance method and it is concluded that the resonant cavity method known as the precise technique to be constructing in characterization of materials. However, the complexity of the structure leads to the high cost of fabrication process even though the Q-factor can be higher. Thus, another design of structure can be suggested which is planar resonant sensor. The design structures are more simple and easy to fabricate but can achieved higher Q-factor with certain techniques. The device can be expanded more bases on its achievement. The research in this area is still ongoing but not so infancy. Some challenges that the researchers faced, is hoped can be overcome and improved in order to gain better upgraded in this technology.

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