Microwave Sensor for Ethanol Intensity Determination Based on Fractal Resonators

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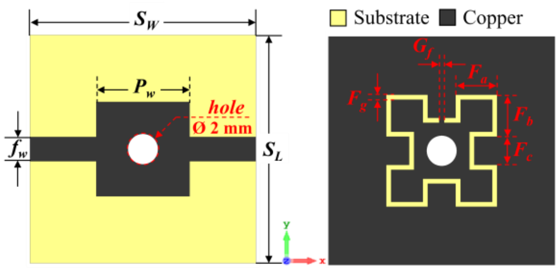
Abstract

This paper presents a fractal resonator and square patch microstrip-line structure with a central drill hole as a means of achieving ethanol concentration characterization. The liquid under test (LUT), which is a binary mixed liquid made up of ethanol and water, is used to measure and detect the effectiveness of the suggested sensor. The LUT was injected into a glass capillary tube that was positioned in the middle of the square patch microstrip-line structure for the ethanol concentration test. The sensors were designed and fabricated on an FR-4 substrate with a thickness of 0.8 mm, highlighting in general measurements of 15 × 15 mm², and operating at 2.50 GHz under an unloaded condition. The detected ethanol concentrations ranging from 10% up to 95% within the ethanol-water mixtures. Measurement comes about demonstrating the sensor's capability to identify ethanol concentration by comparing the shifted resonance frequency within the transmission coefficient.

Keywords: Microwave sensor, Fractal resonator, Ethanol concentration, Ethanol sensor,

1. Introduction

Ethanol, also known as ethyl alcohol, is a type of alcohol chemical with a boiling point of approximately 78°C. It is a flammable liquid, smokeless, easily volatile, hygroscopic, and it's readily mixed with water and methylene chloride. Ethanol finds applications as a reactant or solvent in various industries, including cosmetics, medicine, perfume, and soap production. It is often blended with a fuel to increase octane and reduce the number of certain fuels, such as gasohol. Additionally, it is utilized in alcoholic beverages and used as a disinfectant or wound cleanser, commonly in the



(a) (b)

Figure 1. Geometry of the sensor for ethanol intensity determination (a) front view (b) back view.

form of 75% ethanol. Moreover, ethanol serves as a solvent in industries and pharmaceutical companies, such as in cough medicine production. Due to its diverse properties, therefore the researchers have designed sensors to measure ethanol characteristics.

In recent years, microwave frequencies have been increasingly utilized in sensor design for various applications, including the characterization of glucose [1-2], ammonia gas [3], plastic polymer materials [4], and sodium chloride (NaCl) [5]. Within this realm, the sensors for ethanol characterization have been explored extensively, employing diverse structures such as 3D-printed lenses [6], waveguides [7], split ring resonators [7-8], and fractal structures [9-12]. These structures utilize the transmission coefficient, S_{21}, to discern ethanol concentration characteristics. Notably, fractal structures offer advantages in sensor design by enabling compact size and responsiveness across multiple frequency bands.

This paper introduces a microwave sensor for measuring ethanol concentration, employing a square patch microstrip-line structure and a fractal resonator. The transmission line technique is utilized to characterize liquid content percentage in the mixture, offering broadband measurement suitable for lossy

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materials. The proposed sensor features a drilled hole at its center to bring different ethanol concentrations into a glass capillary tube. Ethanol concentrations ranging from 10% to 95% were measured, with a minimum of three distinct measurements conducted repeatedly to ensure the measurement and sensor accuracy. Importantly, the sensor operates without physical contact, utilizing a non-destructive method, and is characterized by its compactness, affordability, and ease of production.

2. Ethanol Sensor Design and Fabrication

A. Ethanol Sensor Design and Simulation

Figure 1 depicts the microwave sensor's geometry for detecting ethanol concentration. The square patch microstrip-line structure, illustrated in Fig. 1(a), is designed in a front view, while the fractal resonator, depicted in Fig. 1(b), is designed in a back view. Fabricated on an FR-4 substrate measuring 0.8 mm in thickness, with a relative permittivity (ε_r) of 4.4 and a loss tangent of 0.025, the sensors having an overall dimensions of 15 × 15 mm². Designed to operate at 2.50 GHz under unloaded conditions, the square patch features a center drill hole with a diameter of 2 mm, was intended for accommodating a glass capillary tube filled with ethanol as the liquid under test (LUT). The optimized parameter dimensions, detailed in Table 1, were simulated using the 3D EM simulation tool CST Studio Suite.

The simulation of an electric field within the sensor is illustrated in Figure 2, which is presented in the form of a bubble electric field. Ports 1 and 2, the fractal resonator and the hole region have a high electric field intensity. Figure 3 presents the transmission coefficient, S_{21}, obtained from the simulation, comparing the results of three models: the bare ethanol sensor, the ethanol sensor with a tube, and the ethanol sensor with distilled water. In the graph, the bare ethanol sensor (depicted by the black line) demonstrates a resonance frequency of 2.53 GHz and a transmission coefficient, S_{21}, of -23.29 dB. Conversely, the ethanol sensor with a tube (represented by the red dotted line) exhibits a resonance frequency of 2.49 GHz and a transmission coefficient, S_{21}, of -23.76 dB, while the ethanol sensor with distilled water (indicated by the blue line) shows a resonance frequency of 2.43 GHz and a transmission coefficient, S_{21}, of -24.99 dB.

B. Ethanol Sensor Fabrication

The finalized models of the proposed ethanol sensor were exported from the simulation tool, CST microwave studio suite, utilizing the computer-aided design (CAD) file format. Subsequently, the file underwent conversion using computer-aided manufacturing (CAM) software to generate a file compatible with a computer numerical control (CNC) machine. This CNC machine, renowned for its high accuracy, employs a milling process where the blade moves along a defined direction. Especially, it can cut materials ranging from small to large sizes, thereby shaping the workpiece according to production requirements. Following the completion of the milling process, the fabricated prototype of the ethanol sensor was outfitted with a 50-ohm SMA port on both ends. The resulting prototype is depicted in Figure 4. This prototype was then utilized for the measurement of ethanol concentration characterization, which is the next topic of this research paper.

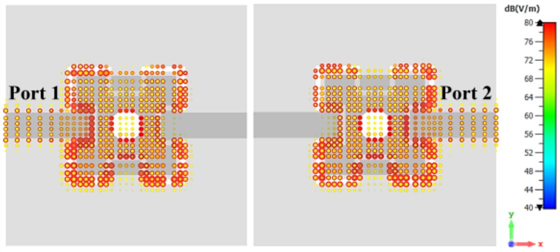

Figure 2. The simulation electric field of the sensor for ethanol intensity determination.

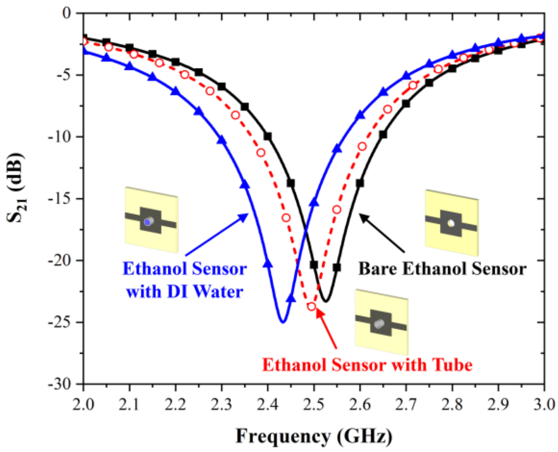

Figure 3. The simulation results of the ethanol sensor transmission coefficient, S_{21}.

Table 1: The dimension of the sensor for ethanol intensity determination is shown in Figure 1

Parameters	Dimension (mm)
S_W	15
S_L	15
P_w	6.2
f_w	1.6
G_f	0.325
F_a	2.75
F_b	2.75
F_c	1.85
F_g	0.325

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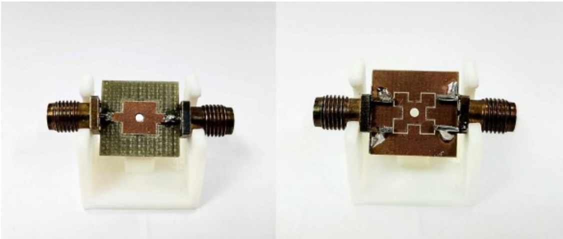

(a) (b)

Figure 4. The fabricated sensors based on fractal structure for measured ethanol concentration (a) front view (b) back view.

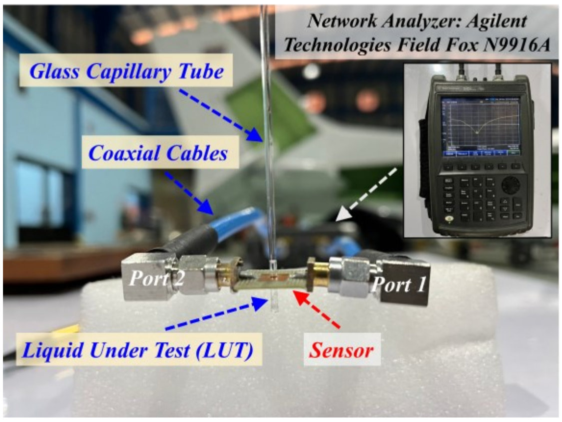

Figure 5. Measurement setup of the ethanol sensor proposed.

3. Measurement Results

A. Measurement Setup

The analysis and testing of ethanol concentration characterization were conducted utilizing the transmission coefficient, S21, measured with an Agilent Technologies FieldFox N9916A vector network analyzer (VNA). The process commenced with the calibration of the FieldFox VNA in two ports using the Through-Open-Short-Match (TOSM) calibration technique. This calibration served to eliminate systematic errors introduced by the FieldFox VNA and connecting cables. The frequency range of the FieldFox VNA was configured from 2 GHz to 3 GHz, and the number of sampling frequency points was 401 points. Figure 5 illustrates the measurement setup employed for ethanol concentration characterization. A glass capillary tube with a diameter of 2 mm was positioned at the center of the sensor and filled with ethanol as the liquid under test (LUT).

To prepare the various ethanol concentrations, ethanol was mixed with distilled water according to the following ratios: 10% ethanol utilized 1 ml of ethanol per 8.5 ml of distilled water, 20% ethanol employed 2 ml of ethanol per 7.5 ml of distilled water, and so forth, up to 95% ethanol, which used 9.5 ml of ethanol per 0 ml of distilled water.

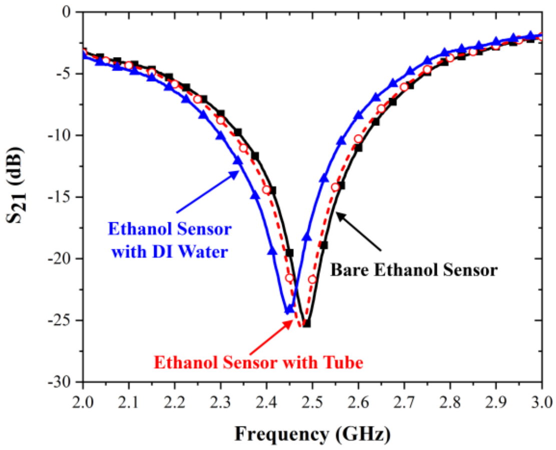

Figure 6. The measurement results of the ethanol sensor transmission coefficient, S_{21}.

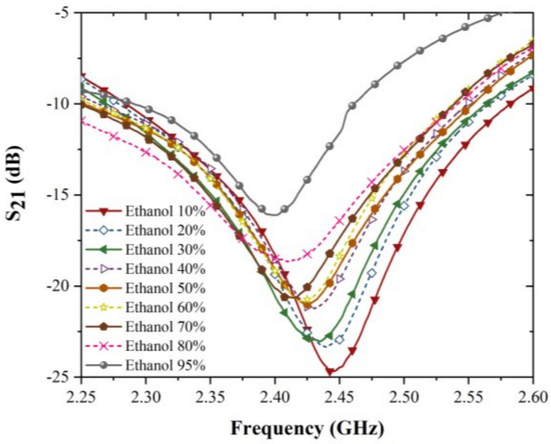

Figure 7. The measured results of the transmission coefficient, S_{21}, of ethanol concentration at 10% - 95%.

Table 2: The comparison measured sensitivity in ethanol concentration of resonance frequency.

Ethanol concentration	Frequency resonance (GHz)	Transmission coefficient, S_{21} (dB)
10%	2.4450	-24.6878
20%	2.4400	-23.4020
30%	2.4350	-23.0642
40%	2.4300	-21.2364
50%	2.4250	-20.9943
60%	2.4200	-20.8454
70%	2.4150	-20.6590
80%	2.4100	-18.6694
95%	2.4025	-16.1156

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To ensure accuracy and repeatability, at least three repeated individual measurements were conducted for each ethanol concentration.

B. Measurement Results

Figure 6 illustrates the measured transmission coefficient, S_{21}, comparing the results obtained from three models: the bare ethanol sensor, the ethanol sensor with a tube, and the ethanol sensor with distilled water. In the graph, the bare ethanol sensor (depicted by the black line) exhibits a frequency resonance of 2.48 GHz and a transmission coefficient, S_{21}, of -25.36 dB. Conversely, the ethanol sensor with a tube (represented by the red dotted line) demonstrates a frequency resonance of 2.47 GHz and a transmission coefficient, S_{21}, of -25.66 dB, while the ethanol sensor with distilled water (indicated by the blue line) shows a frequency resonance of 2.45 GHz and a transmission coefficient, S_{21}, of -24.28 dB. Figure 7 presents the measured results of the transmission coefficient, S_{21}, for ethanol concentrations ranging from 10% to 95%. According to the measurement results, found out that the transmission coefficient, S_{21}, levels vary with different ethanol concentrations. For instance, when the liquid solution contains 10% ethanol, the transmission coefficient, S_{21}, measures -24.69 dB, while for concentrations of 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 95% ethanol, the corresponding transmission coefficient, S_{21}, values are -23.40 dB, -23.06 dB, -21.24 dB, -20.99 dB, -20.85 dB, -20.66 dB, -18.67dB and -16.12 dB, respectively. Furthermore, details of the measurement results can be found in Table 2. Based on these measurement results, it is evident that the level of the transmission coefficient, S_{21}, decreases as the percentage of ethanol in the liquid solution increases.

4. Conclusion

This paper presents a sensor designed for determining ethanol concentration, operating at a frequency of 2.50 GHz under unloaded conditions, commonly referred to as a bare ethanol sensor. The optimal dimensions of the sensor were determined using 3D EM Simulation CST Studio, which facilitated an investigation into the sensor's performance. To characterize ethanol concentration, the sensor relies on detecting the level of the transmission coefficient, S_{21}. The ethanol concentrations examined during experimentation included: 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 95% ethanol solutions. Analysis of the measurement results revealed that the sensor's ability to discriminate between different ethanol concentrations.

References

[1] T. Pechrkool, P. Sangmahamad, P. Thiamsinsangwon, T. Sutham, B. Kumkhet and V. Pirajnanchai, “High-Sensitivity Contactless Microwave Sensor Based on Rectangular Complementary Split Ring Resonator for Glucose Concentration Characterization,” *2022 37th International Technical Conference on Circuits/Systems, Computers and Communications (ITC-CSCC)*, Phuket, Thailand, 2022, pp. 971-974, doi: 10.1109/ITC-CSCC55581.2022.9895084.
[2] S. Chudpooti, P. Sangpet, T. Pechrkool, S. Chalermwisutkul and P. Akkaraekthalin, “Non-Destructive Liquid-Mixture Sensor Using Dual-Mushroom Resonator for Glucose Concentration Characterization,” *2021 Research, Invention, and Innovation Congress: Innovation Electricals and Electronics (RI2C)*, Bangkok, Thailand, 2021, pp. 88-91, doi: 10.1109/RI2C51727.2021.9559803.
[3] W. Krudpun, N. Chudpooti, P. Lorwongtragool, S. Seewattanapon and P. Akkaraekthalin, “PSE-Coated Interdigital Resonator for Selective Detection of Ammonia Gas Sensor,” in *IEEE Sensors Journal*, vol. 19, no. 23, pp. 11228-11235, 1 Dec.1, 2019, doi: 10.1109/JSEN.2019.2936102.
[4] N. Chudpooti, V. Doychinov, B. Hong, P. Akkaraekthalin, I. Robertson and N. Somjit, “Multi-modal millimeter-wave sensors for plastic polymer material characterization,” in *Journal of Physics D: Applied Physics*, Vol. 51, no. 27, 18 June, 2018, doi: 10.1088/1361-6463/aac818.
[5] N. Chudpooti et al., “In-Situ Self-Aligned NaCl-Solution Fluidic-Integrated Microwave Sensors for Industrial and Biomedical Applications,” in *IEEE Access*, vol. 8, pp. 188897-188907, 2020, doi: 10.1109/ACCESS.2020.3031864.
[6] N. Chudpooti, P. Sangpet, N. Duangrit, P. Akkaraekthalin, I. D. Robertson and N. Somjit, “An Integrated 3D-Printed Lens with Ultra-Wideband Flower-Shaped Stub Antenna for Ethanol-Water Mixture Characterization,” *2021 Research, Invention, and Innovation Congress: Innovation Electricals and Electronics (RI2C)*, Bangkok, Thailand, 2021, pp. 80-83, doi: 10.1109/RI2C51727.2021.9559770.
[7] N. Chudpooti, E. Silavwe, P. Akkaraekthalin, I. D. Robertson and N. Somjit, “Nano-Fluidic Millimeter-Wave Lab-on-a-Waveguide Sensor for Liquid-Mixture Characterization,” in *IEEE Sensors Journal*, vol. 18, no. 1, pp. 157-164, 1 Jan.1, 2018, doi: 10.1109/JSEN.2017.2772348.
[8] Y. Song et al., “Metamaterial-Inspired Microwave Sensor for Ethanol Detection,” *2022 10th International Symposium on Next-Generation Electronics (ISNE)*, Wuxi, China, 2023, pp. 1-3, doi: 10.1109/ISNE56211.2023.10221672.
[9] M. Palandoken et al., “Novel Microwave Fluid Sensor for Complex Dielectric Parameter Measurement of Ethanol–Water Solution,” in *IEEE Sensors Journal*, vol. 23, no. 13, pp. 14074-14083, 1 July1, 2023, doi: 10.1109/JSEN.2023.3276817.
[10] C. Gocen and M. Palandoken, “Machine Learning Assisted Novel Microwave Sensor Design for Dielectric Parameter Characterization of Water–Ethanol Mixture,” in *IEEE Sensors Journal*, vol. 22, no. 3, pp. 2119-2127, 1 Feb.1, 2022, doi: 10.1109/JSEN.2021.3136092.
[11] R. K. Abdulsattar, T. A. Elwi and Z. A. A. Hassain, “A Novel Moore Fractal Shaped Microwave Resonator for liquids characterizations,” *2021 7th International Conference on Space Science and Communication (IconSpace)*, Selangor, Malaysia, 2021, pp. 271-274, doi: 10.1109/IconSpace53224.2021.9768732.
[12] A. Arif, A. Zubair, K. Riaz, M. Q. Mehmood and M. Zubair, “A Novel Cesaro Fractal EBG-Based Sensing Platform for Dielectric Characterization of Liquids,” in *IEEE Transactions on Antennas and Propagation*, vol. 69, no. 5, pp. 2887-2895, May 2021, doi: 10.1109/TAP.2020.3028201.

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