BUKTI REVIEW DAN CORRESPONDING AUTHOR

SYARAT KHUSUS UNTUK PENGUSULAN JABATAN AKADEMIK

UNIVERSITAS TRISAKTI

Judul Paper	:	Dual Functional Liquid Displacement and Angular Detection Based on Band Stop Response Microwave Sensor
Nama Penulis	:	**Syah Alam**; Indra Surjati; Lydia Sari; R Deiny Mardian; Marouane Abicha; Zahriladha Zakaria; Teguh Firmansyah; Mudrik Alaydrus; Yusnita Rahayu
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1st submission → Major Revision

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Dual Functional Liquid Displacement and Angular Detection Based on Band Stop Response Microwave Sensor

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Journal Contacts	Sharma, Dr. Dharmendra - Administrator dharmendra.sharma@ieee.org

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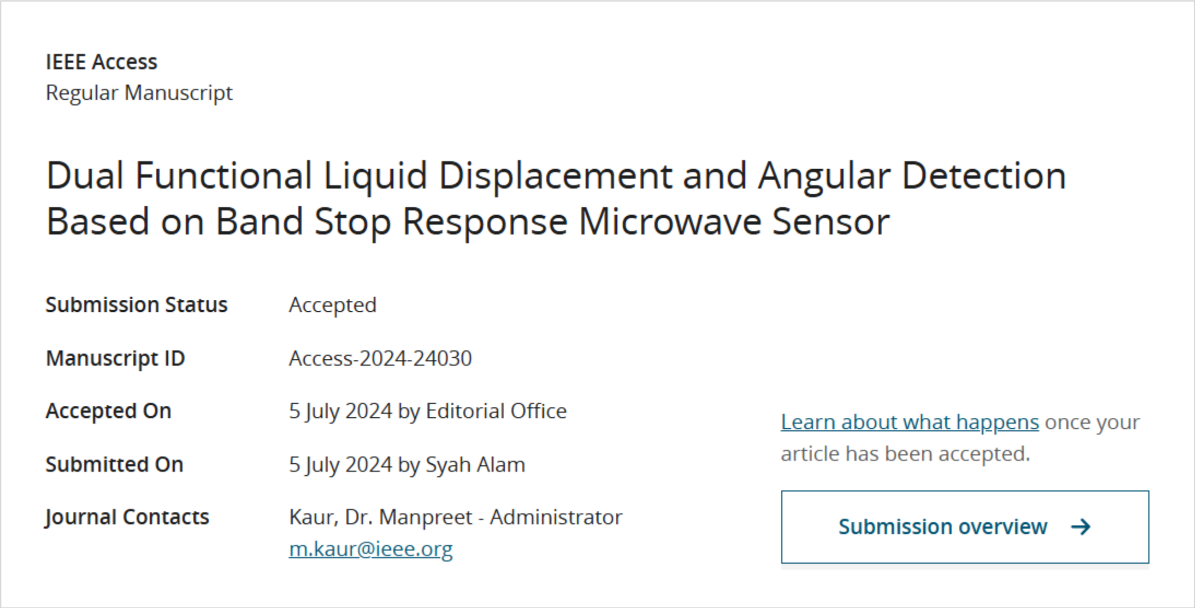
2nd submission → Accepted



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1 message

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21-Jun-2024

Dear Authors:

Your manuscript entitled "Dual Functional Liquid Displacement and Angular Detection Based on Band Stop Response Microwave Sensor" has been successfully submitted online and is presently being given full consideration for publication in IEEE *Access*.

If you are receiving this email, that means you are listed as an author. If you do **not** approve of being listed as a co-author on this article, please reach out to ieeeaccesseic@ieee.org as soon as possible.

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Decision 1st round

Decision letter (Initial Submission)

Dual Functional Liquid Displacement and Angular Detection Based on Band Stop Response Microwave Sensor

Subject IEEE Access - Decision on Manuscript ID Access-2024-17163
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21-May-2024

Dear Dr. Alam:

I am writing to you regarding manuscript # Access-2024-17163 entitled "Dual Functional Liquid Displacement and Angular Detection Based on Band Stop Response Microwave Sensor" which you submitted to IEEE *Access*.

Your article was peer reviewed with interest but has not been recommended for publication in its current form. We strongly encourage you to address the reviewers' concerns, which can be found at the bottom of this letter, and resubmit your article to IEEE *Access* once you have updated it accordingly.

Please note that IEEE *Access* has a binary peer review process. Therefore, to uphold quality to IEEE standards, an article is rejected even if it requires minor edits.

When updating your manuscript, you should elaborate on your points and clarify with references, examples, data, etc. If you disagree with any technical points the reviewers have made, please include your counterarguments in your response to the reviewers (more information detailed below) and work this into the updated manuscript. Also, note that if a reviewer suggested references, you should only add those that are relevant to your work if you feel they strengthen your article. Recommending references to specific publications is not appropriate for reviewers and you should report excessive cases to ieeeaccessEIC@ieee.org.

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2) Your updated manuscript with all your individual changes highlighted, including grammatical changes (e.g. preferably with the yellow highlight tool within the pdf file). This file should be uploaded with your manuscript files as *"Highlighted PDF."*

3) A clean copy of the final manuscript (without highlighted changes) submitted as a Word or LaTeX file, and as a PDF, both submitted as the "*Main Manuscript*."

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We sincerely hope you will update your manuscript and resubmit soon. Please contact me if you have any questions.

Thank you for your interest in IEEE *Access*.

Sincerely,

Dr. LI YANG
Associate Editor, IEEE *Access*
yang96507@gmail.com

Reviewers' Comments to Author:

Reviewer: 1

Comments:
The manuscript deals with a dual functional microwave sensor for displacement and angular detectionof liquid material based on electric coupled (ELC) resonator. The experimental work is well explained and illustrated with manymeasured results.

Additional Questions:
Please confirm that you have reviewed all relevant files, including supplementary files and any author response files, which can be found in the "View Author's Response" link above (author responses will only appear for resubmissions): Yes, all files have been reviewed

1) Does the paper contribute to the body of knowledge?: yes

2) Is the paper technically sound?: yes

3) Is the subject matter presented in a comprehensive manner?: yes

4) Are the references provided applicable and sufficient?: N/A

5) Are there references that are not appropriate for the topic being discussed?: No

5a) If yes, then please indicate which references should be removed.:

Reviewer: 2

Comments:
The sensor works by changing the dielectric loading on top of a microstrip-based ELC resonator, thereby altering the resonant frequency of the circuit. By measuring the transmission zero location, the sensor can be used for determining the displacement of the dielectric loading. The loading in this work is a tube of water on top of the resonator, and by changing the water fill level, it causes a change in the equivalent LC of the circuit. Since water has a large dielectric constant, the impact on the resonant frequency is significant.

Here are some specific comment and questions:

1. Though the application for angular displacement of liquid seems novel, can you cite the applications where this is useful?

2. Page 7 of 28: “The measurement process was carried out in the laboratory using a Vector Network Analyzer (VNA) with a frequency range of 2 - 3 GHz, a frequency span of 0.01 GHz and an ambient temperature of 25°C.” It shouldn’t be frequency span. It could be frequency step size, resolution/video bandwidth, but not span.

3. Page 7 of 28 Eq. (2) cites ref [18] for an equation to determine displacement from resonant frequency. Although the authors did not elaborate, Eq(2) is a curve-fitted equation using either simulation or measurement. Ref [18] instead uses an analytical method. Therefore, the citation is not valid.

4. Page 10 of 28. Table 10 compares different microwave sensors that measure linear and angular displacement. Ensure that the comparison is clear and the context of each sensor’s application is adequately explained.

5. The authors claim that the sensor uses a microfluidic channel, which is characterized by small volumes (μL, nL, pL, fL) and has a small size; however, this design in the manuscript uses a drinking straw, which has a volume in the range of mL. This discrepancy needs to be addressed.

6. Given that the angular displacement sensing uses bending of the straw to achieve rotation, the repeatability of the measurement and the precision come into question. Please address this issue.

7. Most of the other displacement sensors cited use metal on top of a stable dielectric substrate. This work uses a dielectric instead. This is a novelty in itself, but the co-sensitivity to temperature needs to be discussed. The other sensors use stable substrates which might offer better temperature stability.

Additional Questions:
Please confirm that you have reviewed all relevant files, including supplementary files and any author response files, which can be found in the "View Author's Response" link above (author responses will only appear for resubmissions): Yes, all files have been reviewed

1) Does the paper contribute to the body of knowledge?: Yes, the paper contributes to the body of knowledge by introducing a dual-functional microwave sensor capable of detecting both linear and angular displacement of liquid samples using microfluidic channels. This is a novel approach as previous works have primarily focused on solid materials and have not combined both displacement and angular detection for liquid materials in a single sensor.

2) Is the paper technically sound?: The paper is technically sound, presenting an experimental setup and clear methodology for the proposed sensor. The use of an ELC resonator and microfluidic channels is adequately justified, and the results are supported by experimental data. However, there are some technical inaccuracies in the references and certain methodological explanations that need correction and clarification to enhance the paper's robustness.

3) Is the subject matter presented in a comprehensive manner?: Yes

4) Are the references provided applicable and sufficient?: The references provided are generally applicable and sufficient, covering a wide range of

relevant studies in the field of microwave sensors for displacement and angular detection. However, there are a few issues with specific citations, such as the incorrect reference for Equation (2) and the need for more precise and relevant sources in some sections. Addressing these issues would strengthen the overall quality and credibility of the paper.

5) Are there references that are not appropriate for the topic being discussed?: No

5a) If yes, then please indicate which references should be removed.:

If you have any questions, please contact article administrator: Dr. Dharmendra Sharma dharmendra.sharma@ieee.org

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Response 1st round

Original Manuscript ID: Access-2024-17163

Original Article Title: "Dual Functional Liquid Displacement and Angular Detection Based on Band Stop Response Microwave Sensor"

To:

Dr. Lie Yang

IEEE Access Editor

Re: Response to reviewers

Dear Editor,

Thank you for allowing a resubmission of our manuscript, with an opportunity to address the reviewers' comments.

We are uploading (a) our point-by-point response to the comments (below) (response to reviewers, under "Author's Response Files"), (b) an updated manuscript with yellow highlighting indicating changes (as "Highlighted PDF"), and (c) a clean updated manuscript without highlights ("Main Manuscript"*).*

We sincerely appreciate the valuable time you dedicated to reviewing and evaluating our paper. Should you have any queries, please feel free to reach out to me. Thank you again for your time and consideration.

Best regards,

Syah Alam, et al.

Please address all correspondence to:

Syah Alam* / Zahriladha Zakaria**

*Department of Electrical Engineering, Universitas Trisakti, DKI Jakarta, 11440

** Faculty of Electronic and Computer Technology and Engineering, Universiti Teknikal Malaysia Melaka (UTeM), Malaysia

Corresponding author e-mail: *syah.alam@trisakti.ac.id / ** zahriladha@utem.edu.my

Reviewer#1, Concern # 1:

The manuscript deals with a dual functional microwave sensor for displacement and angular detection of liquid material based on electric coupled (ELC) resonator. The experimental work is well explained and illustrated with many measured results.

Author response: We thank the reviewer for constructive comment.

Reviewer#2, Concern # 1:

Though the application for angular displacement of liquid seems novel, can you cite the applications where this is useful?

Author response: We thank the reviewer for constructive comment. Therefore, we have added some previous research to show the applications of liquid displacement, including biomedical and robotics [30], health monitoring and mobile healthcare [31].

Author action: We updated the manuscript by added new reference [30] and [31] in the introduction section

Kindly refer to: Section I. Introduction, page 1 – 2

"Displacement sensors play an important role for several industries that require high precision such as the automotive, robotics and aerospace industries[1][2][3][4]. Generally, displacement sensors consist of two types, including linear and angular displacement. Linear displacement is determined based on distance while angular displacement is based on the angle between the sensor and the sample[5][6]. One of the strategies for detecting sample displacement is to utilize a microwave sensor[7][8][9][10]. Microwave sensors have advantages including compact design, low cost and high accuracy. Microwave sensors have been widely developed to detect the characteristics of solid materials [11]–[13], liquids[14]–[17] and displacement[18]–[20]. Several previous works proposed sensors for linear and angular displacement detection in solid materials using microwave sensors with a certain dynamic range based on frequency shift[21][22], notch depth [23][24] and phase variation[25][26].

Generally, rotation and displacement detection using microwave sensors is proposed for solid materials using stators and rotators where the sample is rotated in the sensing area with a certain dynamic range[27]–[29]. However, this creates friction between the sample and the sensor which has the potential to damage the surface of the sensor. In addition, the sample is placed on an open surface, so it is greatly influenced by changes in temperature and environment. Another constraint, the proposed sensor from previous work only has one single function so it cannot be used for displacement and rotation detection separately. In addition, sensors for displacement and rotation detection are only proposed for solid materials and are not supported for detection in liquid samples. Moreover, liquid displacement sensors are very useful for several applications, including biomedical and robotics [30], health monitoring and mobile healthcare[31]. Therefore, microwave sensors that have the capability to detect displacement and rotation of liquid samples are needed. This work provides an excellent solution by proposing a microwave sensor that has dual functional characteristics for displacement and angular detection for liquid samples. Furthermore, to maintain and control the influence of temperature and environment, the sample is contained in a microfluidic channel[32]–[34]. Moreover, microfluidic channels are proposed to reduce friction between the sensor and the sample so that the sensor surface is more durable and protected. Displacement and angular detection are determined based on the shift in the resonant frequency of the resonator.

The main contribution of this work is to produce a dual functional microwave sensor that has the capability for displacement and angular detection in liquid samples in microfluidic channels. The proposed sensor has been successfully simulated and validated through the measurement process. Based on the measurement results, the proposed sensor has the ability to detect displacement with a distance range of 1 - 4 cm and for angular detection with an angle range of 0 - 90° for microfluidic channel filled with water content."

Reference:

[30] G. Keulemans, F. Ceyssens, and R. Puers, "An ionic liquid based strain sensor for large displacement measurement," Biomed. Microdevices, vol. 19, no. 1, 2017, doi: 10.1007/s10544-016-0141-4.

[31] Y. Ren, S. Tan, L. Zhang, Z. Wang, Z. Wang, and J. Yang, "Liquid level sensing using commodity wifi in a smart home environment," Proc. ACM Interactive, Mobile, Wearable Ubiquitous Technol., vol. 4, no. 1, pp. 1–30, 2020, doi: 10.1145/3380996.

Reviewer#2, Concern # 2:

Page 7 of 28: "The measurement process was carried out in the laboratory using a Vector Network Analyzer (VNA) with a frequency range of 2 - 3 GHz, a frequency span of 0.01 GHz and an ambient temperature of 25°C." It shouldn't be frequency span. It could be frequency step size, resolution/video bandwidth, but not span.

Author response: We thank the reviewer for constructive comment. We have changed the term of frequency span to frequency step size according to comments from reviewers. We thank you for the corrections provided.

Author action: We updated the manuscript by changing the term of frequency span to frequency step size in section III. Measurement and Verification on page 4.

Kindly refer to: Section III. Measurement and Verification, page 4

III. MEASUREMENT RESULT AND VERIFICATION
In this chapter, the measurement process and scenarios for liquid displacement and angular detection are explained in detail. The measurement process was carried out in the laboratory using a Vector Network Analyzer (VNA) with a frequency range of 2 - 3 GHz, a frequency step size of 0.01 GHz and an ambient temperature of 25°C.

Reviewer#2, Concern # 3:

Page 7 of 28 Eq. (2) cites ref [18] for an equation to determine displacement from resonant frequency. Although the authors did not elaborate, Eq (2) is a curve-fitted equation using either simulation or measurement. Ref [18] instead uses an analytical method. Therefore, the citation is not valid.

Author response: We thank the reviewer for constructive comment. In this paper, liquid displacement detection is proposed using a polynomial curve by observing the frequency shift of the measurement process relative to the displacement of the sample. Therefore, Eq (2) is obtained from the frequency response to sample shift from the measurement process. Furthermore, we have changed reference [18] to [7] which is related to polynomial curves for detecting displacements in samples.

Author action: We updated the manuscript by giving a clear explanation about the polynomial curve for displacements detection and changed the reference [18] to [7] which is related to polynomial curves for detecting displacements in samples.

Kindly refer to: Section III. Measurement and Verification, Sub Section: A. Scenario for liquid displacement detection, page 4.

*"Based on the measurement results, the resonant frequency of the resonator shifts from 2.72 GHz to 2.59 GHz with ΔF of 0.13 GHz in line with the sample displacement in the microfluidic channel which is clogged by a stopper with a distance range of d = 1 - 4 cm as shown in **Fig.8 (a)** and **Fig.8 (b)**. This finding shows that the proposed sensor has interacted with the sample to detect the displacement of the sample. The resonant frequency of the resonator shifts to low frequencies slowly in line with the displacement of the sample. This occurs because there is a change in the permittivity of the sample, where the water sample has a higher permittivity than the bare air sample, so it greatly influences the resonance frequency of the resonator. Furthermore, displacement detection with the proposed resonator can be determined based on **Eq. (2)**[7]:*

$$\boldsymbol{f_{r\,(c)} = 0.01273\, d^3 - 0.988\, d^2 + 0.1862\, d - 2.6153} \qquad (2)$$

*where $f_{r\,(b)}$ is the resonant frequency of the resonator for displacement detection and d represents the distance of the displacement in the water-filled microfluidic channel. Moreover, the sensitivity (S) of the sensor is determined based on the following **Eq. (3)**[21]:*

$$\boldsymbol{S = \frac{\Delta F\ (GHz)}{\Delta d\ (cm)}} \qquad (3)$$

*where ΔF represents the shift in the resonant frequency of the resonator and Δd represents the displacement of the sample in the microfluidic channel. Based on **Eq. (3)**, the sensitivity of the sensor for displacement detection is 32.5 MHz/cm with a range d of 1 - 4 cm."*

Reference:

[7] A. V. Praveen Kumar and P. Regalla, "A Transmission Mode Dielectric Resonator as a Displacement Sensor," *IEEE Sens. J.*, vol. 20, no. 13, pp. 6979–6984, 2020, doi: 10.1109/JSEN.2020.2977893.

Reviewer#2, Concern # 4

Page 10 of 28. Table 10 compares different microwave sensors that measure linear and angular displacement. Ensure that the comparison is clear, and the context of each sensor's application is adequately explained.

Author response: We thank the reviewer for constructive comment. We have comprehensively explained the comparison of type, sensing parameters and prospective applications between the proposed sensor and previous work shown in Table 3.

TABLE III
COMPARISON OF TYPE, SENSING PARAMETERS AND PROSPECTIVE APPLICATIONS OF DISPLACEMENT / ROTATION SENSORS

Ref	Type of resonator	Sensing parameter	Prospective applications
[1]	Single port resonator	Phase	Industrial
[3]	Band stop filter	S_{21}	Industrial
[7]	Band pass filter	S_{21}	Industrial
[19]	Band stop filter	S_{21}	Industrial
[21]	Band stop filter	S_{21}	Space vehicle (satellites)
[23]	Band pass filter	Phase	Industrial
[27]	Band pass filter	S_{21}	Industrial
[28]	Band stop filter	S_{21}	Industrial
[32]	Band pass filter	S_{21}	Biomedical and energy
This work	Band stop filter	S_{21}	Industrial and Biomedical

Furthermore, a comprehensive comparison of types, sensing parameters and proposed applications of displacement and rotation sensors is shown in Table III. Previous work [3][19][21][23} proposed a band stop filter for displacement and rotation detection which is recommended for industrial applications including flow detection in liquids, space vehicle and rotation detection in AC motors. In addition, other work [7][23][27][32] proposed a band stop filter for displacement/rotation detection which is recommended for industrial, biomedical and energy applications while previous work [1], proposed a single port resonator for motor rotation detection AC based on phase variations.

Author action: We updated the manuscript by providing clear information regarding the comparison of the proposed sensor with previous work which is presented in Table III.

Kindly refer to: Section IV. Validation with previous work, Table III. COMPARISON OF TYPE, SENSING PARAMETERS AND PROSPECTIVE APPLICATIONS OF DISPLACEMENT / ROTATION SENSORS, page 7.

Furthermore, a comprehensive comparison of types, sensing parameters and proposed applications of displacement and rotation sensors is shown in Table III. Previous work [3][19][21][23} proposed a band stop filter for displacement and rotation detection which is recommended for industrial applications including flow detection in liquids, space vehicle and rotation detection in AC motors. In addition, other work [7][23][27][32] proposed a band stop filter for displacement/rotation detection which is recommended for industrial, biomedical and energy applications while previous work [1], proposed a single port resonator for motor rotation detection AC based on phase variations.

TABLE III

COMPARISON OF TYPE, SENSING PARAMETERS AND PROSPECTIVE APPLICATIONS OF DISPLACEMENT / ROTATION SENSORS

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[21]	Band stop filter	S_{21}	Space vehicle (satellites)
[23]	Band pass filter	Phase	Industrial
[27]	Band pass filter	S_{21}	Industrial
[28]	Band stop filter	S_{21}	Industrial
[32]	Band pass filter	S_{21}	Biomedical and energy
This work	Band stop filter	S_{21}	Industrial and Biomedical

Reference:

[1] J. Muñoz-Enano, P. Vélez, L. Su, M. Gil-Barba, and F. Martín, “A Reflective-Mode Phase-Variation Displacement Sensor,” *IEEE Access*, vol. 8, pp. 189565–189575, 2020, doi: 10.1109/ACCESS.2020.3031032.

[3] P. W. Zhu *et al.*, “Design of H-shaped planar displacement microwave sensors with wide dynamic range,” *Sensors Actuators A Phys.*, vol. 333, p. 113311, 2022, doi: 10.1016/j.sna.2021.113311.

[7] A. V. Praveen Kumar and P. Regalla, “A Transmission Mode Dielectric Resonator as a Displacement Sensor,” *IEEE Sens. J.*, vol. 20, no. 13, pp. 6979–6984, 2020, doi: 10.1109/JSEN.2020.2977893.

[19] C. H. Chio, R. Gomez-Garcia, L. Yang, K. W. Tam, W. W. Choi, and S. K. Ho, “An Angular Displacement Sensor Based on Microwave Transversal Signal Interference Principle,” *IEEE Sens. J.*, vol. 20, no. 19, pp. 11237–11246, 2020, doi: 10.1109/JSEN.2020.2998181.

[21] A. K. Jha, N. Delmonte, A. Lamecki, M. Mrozowski, and M. Bozzi, “Design of Microwave-Based Angular Displacement Sensor,” *IEEE Microw. Wirel. Components Lett.*, vol. 29, no. 4, pp. 306–308, 2019, doi: 10.1109/LMWC.2019.2899490.

[23] J. Naqui and F. Martin, “Transmission lines loaded with bisymmetric resonators and their application to angular displacement and velocity sensors,” *IEEE Trans. Microw. Theory Tech.*, vol. 61, no. 12, pp. 4700–4713, 2013, doi: 10.1109/TMTT.2013.2285356.

[27] C. H. Chio, K. W. Tam, and R. Gomez-Garcia, “Filtering Angular Displacement Sensor Based on Transversal Section with Parallel-Coupled-Line Path and U-Shaped Coupled Slotline,” *IEEE Sens. J.*, vol. 22, no. 2, pp. 1218–1226, 2022, doi: 10.1109/JSEN.2021.3133452.

[28] A. Ebrahimi, W. Withayachumnankul, S. F. Al-Sarawi, and D. Abbott, “Metamaterial-inspired rotation sensor with wide dynamic range,” *IEEE Sens. J.*, vol. 14, no. 8, pp. 2609–2614, 2014, doi: 10.1109/JSEN.2014.2313625.

[32] M. H. Zarifi, H. Sadabadi, S. H. Hejazi, M. Daneshmand, and A. Sanati-Nezhad, “Noncontact and Nonintrusive Microwave-Microfluidic Flow Sensor for Energy and Biomedical Engineering,” *Sci. Rep.*, vol. 8, no. 1, pp. 1–10, 2018, doi: 10.1038/s41598-017-18621-2.

Reviewer#2, Concern # 5:

The authors claim that the sensor uses a microfluidic channel, which is characterized by small volumes (μL, nL, pL, fL) and has a small size; however, this design in the manuscript uses a drinking straw, which has a volume in the range of mL. This discrepancy needs to be addressed.

Author response: We thank the reviewer for constructive comment. We agree with the reviewer's comments regarding the microfluidic approach we have proposed in this paper does not correspond to the recommended sample volumes for microfluidic channels (μL, nL, pL, fL). Therefore, we have replaced the term microfluidic with polystyrene-mm pipe channel referring to previous work [17].

Author action: We updated the manuscript by replacing the term microfluidic with polystyrene-mm pipe channel throughout the revised manuscript.

Kindly refer to: Section II. Working principle of proposed sensor, Sub-section D. Scenario of sample placement, page 3.

D. SCENARIO OF SAMPLE PLACEMENT

The sample placement scenario is determined based on the location of the resonator with the highest electric field as shown in **Fig.6 (a).** In this paper, the sample is placed in the center of the ELC resonator using a polystyrene-mm pipe channel based on polystyrene-mm pipe channel [17] with a permittivity of 3.1 and a diameter represented by D_1 and D_2 of 5 mm and 4.5 mm and length of polystyrene-mm pipe channel represented by L_t of 40 mm, respectively. The sample placement scenario consists of two conditions, including the bare condition where the polystyrene-mm pipe channel is filled with air samples and the other condition is when the polystyrene-mm pipe channel is filled with water samples. The polystyrene-mm pipe channel is placed in line with the sensing area of the ELC resonator which is located in the middle arm and the gap of the resonator.

Reference:
[17] S. Mosbah *et al.*, "Compact and Highly Sensitive Bended Microwave Liquid Sensor Based on a Metamaterial Complementary Split-Ring Resonator," *Appl. Sci.*, vol. 12, no. 4, 2022, doi: 10.3390/app12042144.

Reviewer#2, Concern # 6:

Given that the angular displacement sensing uses bending of the straw to achieve rotation, the repeatability of the measurement and the precision come into question. Please address this issue.

Author response: We thank the reviewer for constructive comment. We agree with the reviewer's comments to perform repeatable measurements of rotation detection using the proposed sensor. Therefore, we have added repeated measurement data to demonstrate the performance of the proposed sensor in Fig 16, page 7. In this experiment, we proposed repeatability measurements for 3 cycles within 5 minutes as shown in **Fig. 2.**

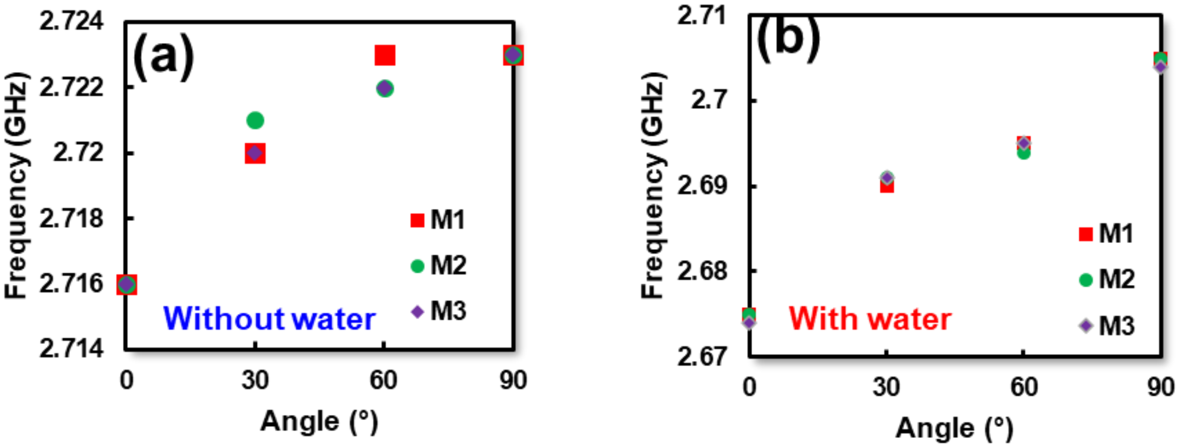

Fig.2 Repeatability measurement of bending detection; (a) without water, (b) with water

Fig. 2 shows that the repeatability measurements of 3 cycles of the proposed sensor are in line and consistent. Furthermore, based on repeatability from measurement 1, 2 and 3 (M1, M2 and M3), the correlation between average resonant frequency and deviation is shown in **Table III**, **Table IV** and **Fig.3**.

Table III. Repeatability measurement of bending detection for sample without water

Angle (º)	f_r (GHz)			Average of f_r (GHz)	Deviation
	M1	M2	M3		
0	2.716	2.716	2.716	2.716	0.00000
30	2.72	2.721	2.72	2.720	0.00058
60	2.723	2.722	2.722	2.722	0.00058
90	2.723	2.723	2.723	2.723	0.00000

Table IV. Repeatability measurement of bending detection for sample with water

Angle (º)	f_r (GHz)			Average of f_r (GHz)	Deviation
	M1	M2	M3		
0	2.675	2.675	2.674	2.675	0.00058
30	2.69	2.691	2.691	2.691	0.00058
60	2.695	2.694	2.695	2.695	0.00058
90	2.705	2.705	2.704	2.705	0.00058

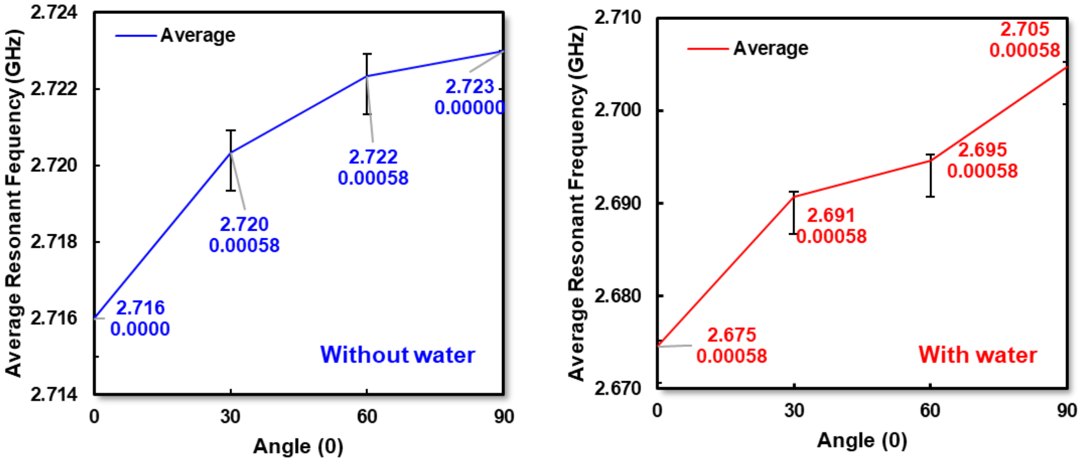

Fig.3 Average and deviation from repeatability measurement for bending detection; (a) without water, (b) with water.

Based on **Fig. 3**, the deviation from the repeatability measurement results is in the range 0 - 0.00058. These findings indicate that the proposed sensor has high accuracy for bending detection in samples with and without water. Therefore, we added these findings in a revised paper represented in Fig. 5 and 6.

Author action: We updated the manuscript by adding Fig. 16 (a) and Fig. 16 (b) to demonstrate repeatability of the measurement.

Kindly refer to: Section III. Measurement and Verification, Sub Section B: Liquid Angular Detection, Fig. 16, page 6.

*Based on **Eq. (6)**, the sensitivity of the sensor for angular detection of microfluidic channel without and with water content are 0.07 MHz/° and 0.33 MHz/° with a dynamic range of 0 - 90°. Moreover, average and deviation of repeatability measurements with 3 cycles are proposed to show the error bars of angular detection for sample filled in microfluidic channel with and without water using the proposed sensor as shown in **Fig.16**.*

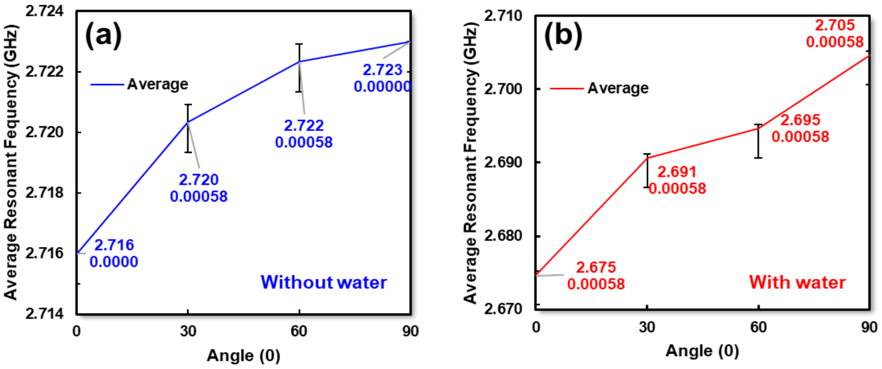

Fig.16. Average and deviation from repeatability measurement for angular detection; (a) without water, (b) with water.

*Based on **Fig.16 (a)** and **Fig. 16 (b)**, the deviation from the repeatability measurement results is in the range 0 - 0.00058 for angular detection with and without water. These findings indicate that the proposed sensor has a low error bar for angular detection in samples with and without water.*

Reviewer#2, Concern # 7:

Most of the other displacement sensors cited use metal on top of a stable dielectric substrate. This work uses a dielectric instead. This is a novelty in itself, but the co-sensitivity to temperature needs to be discussed. The other sensors use stable substrates which might offer better temperature stability.

Author response: We thank the reviewer for constructive comment. For your information, we have tried our best to minimize environmental effects, maintain the temperature of samples at 25^0 C and ensure that there are no other objects close to the sensor during the measurement process in the laboratory.

We thank the reviewer for constructive comments. We agree with the reviewer's comments that the temperature of the sample affects the performance and sensitivity of the sensor. Therefore, we have carried out measurements for liquid displacement detection at three different temperatures of samples at 25^0 C, 27^0C and 30^0 C as shown in **Fig.1** and **Table 1.**

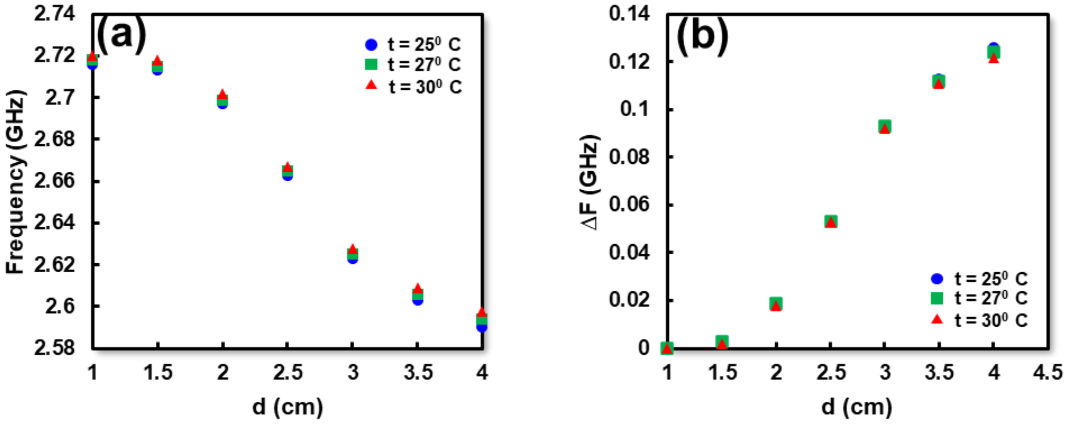

Fig.1 Displacement detection of liquid samples based on different temperatures; (a) response of the resonant frequency, (b) ΔF of proposed sensor.

Table 1. Measurement result of displacement detection based on different temperatures.

d	Frequency (GHz)			Delta F (GHz)		
	t = 25°C	t = 27°C	t = 30°C	t = 25°C	t = 27°C	t = 30°C
1	2.716	2.718	2.72	0	0	0
1.5	2.713	2.715	2.718	0.003	0.003	0.002
2	2.697	2.699	2.702	0.019	0.019	0.018
2.5	2.663	2.665	2.667	0.053	0.053	0.053
3	2.623	2.625	2.628	0.093	0.093	0.092
3.5	2.603	2.606	2.609	0.113	0.112	0.111
4	2.59	2.594	2.598	0.126	0.124	0.122

Based on Fig.1 (a), changes in temperature in the sample have an impact on shifting the resonant frequency of the resonator towards high frequencies correlated with previous work [34] [39]. For example, the resonant frequency of the sensor shifts from 2.716 GHz to 2.718 GHz and 2.72 GHz for temperature changes of 25^0 C, 27^0C and 30^0 C as shown in **Table I**. The maximum ΔF of the proposed sensor for three different temperatures are 0.126 GHz, 0.124 GHz and 0.122 GHz respectively as shown in **Fig. 1 (b)**. The sensitivity of the sensor based on temperature changes is 31.5 MHz/cm, 31 MHz/cm and 30.5 MHz/cm respectively. These findings indicate that changing the temperature of the sample has an impact on the shift in the resonance frequency and sensitivity of the sensor but is not significant. Therefore, the effect of large variations in temperature changes can be further investigated thoroughly in the future in order to understand the behavior of the materials' properties.

Author action: We updated the manuscript by adding new data from the displacement detection measurement process on samples with different temperatures shown in Fig. 17 (a) and Fig. 17 (b), page 9. We have also added a new reference [39] to validate the measurement result.

Kindly refer to: Section III. Measurement and Verification, Sub Section B: Liquid Angular Detection, Fig. 17, page 6.

*Referring to **Fig.17 (a)**, changes in temperature in the sample have an impact on shifting the resonant frequency of the resonator towards high frequencies correlated with previous work [34] [39] . The maximum ΔF of the proposed sensor for three different temperatures are 0.126 GHz, 0.124 GHz and 0.122 GHz respectively as shown in **Fig. 17 (b)**. The sensitivity of the sensor based on temperature changes is 31.5 MHz/cm, 31 MHz/cm and 30.5 MHz/cm respectively. These findings indicate that changing the temperature of the sample has an impact on the shift in the resonance frequency and sensitivity of the sensor but is not significant. Therefore, the temperature of the sample must be verified before the measurement process is carried out to obtain optimal performance.*

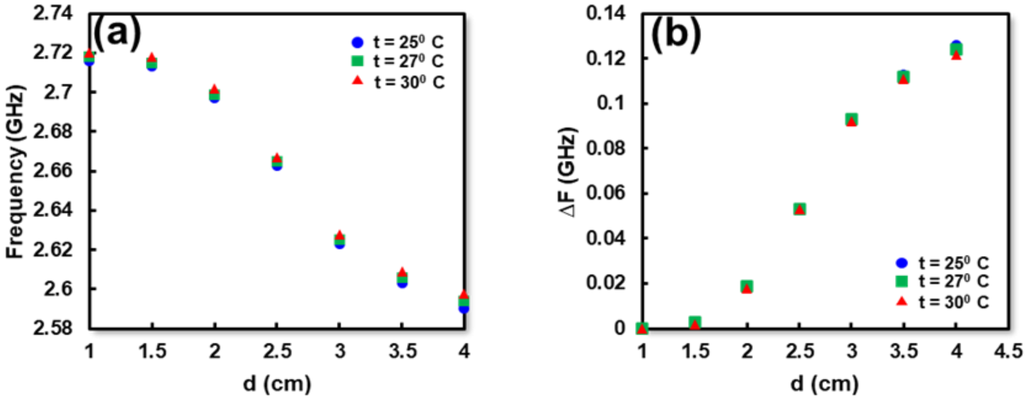

Fig. 17. Displacement detection of liquid samples based on different temperatures; (a) response of the resonant frequency, (b) ΔF of proposed sensor.

Reference:

[34] A. A. Abduljabar, H. Hamzah, and A. Porch, "Double Microstrip Microfluidic Sensor for Temperature Correction of Liquid Characterization," *IEEE Microw. Wirel. Components Lett.*, vol. 28, no. 8, pp. 735–737, 2018, doi: 10.1109/LMWC.2018.2849218.

[39] A. A. Abduljabar, N. Clark, J. Lees, and A. Porch, "Dual Mode Microwave Microfluidic Sensor for Temperature Variant Liquid Characterization," *IEEE Trans. Microw. Theory Tech.*, vol. 65, no. 7, pp. 2572–2582, 2017, doi: 10.1109/TMTT.2016.2647249.

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Dual Functional Liquid Displacement and Angular Detection Based on Band Stop Response Microwave Sensor

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ABSTRACT This paper proposes dual functional microwave sensor for displacement and angular detection of liquid material based on electric coupled (ELC) resonator. The liquid was placed in polystyrene-mm pipe channel filled with water content. The proposed resonator uses a two-port band stop filter operating at a resonant frequency of 2.72 GHz. Polystyrene-mm pipe channels are used to accommodate water samples placed in the sensing area of the sensor in the center of the ELC resonator. Displacement and angular detection were observed based on the shift in the resonant frequency of the resonator. Based on the measurement results, the proposed sensor has a sensitivity for displacement detection of 31.5 MHz/cm with a distance range of d = 1 – 4 cm while for angular detection it is 0.33 MHz/° with a rotation angle of 0 – 90° for polystyrene-mm pipe channel filled with water content. This paper makes a significant contribution by proposed a dual functional microwave sensor for displacement and angular detection that can be recommended for the automotive, robotics and aerospace industries.

INDEX TERMS dual functional, displacement, angular, polystyrene-mm pipe, microwave sensor

I. INTRODUCTION

Displacement sensors play an important role for several industries that require high precision such as the automotive, robotics and aerospace industries[1][2][3][4]. Generally, displacement sensors consist of two types, including linear and angular displacement. Linear displacement is determined based on distance while angular displacement is based on the angle between the sensor and the sample[5][6]. One of the strategies for detecting sample displacement is to utilize a microwave sensor[7][8][9][10]. Microwave sensors have advantages including compact design, low cost and high accuracy. Microwave sensors have been widely developed to detect the characteristics of solid materials [11]–[13], liquids[14]–[17] and displacement[18]–[20]. Several previous works proposed sensors for linear and angular displacement detection in solid materials using microwave sensors with a certain dynamic range based on frequency shift[21][22], notch depth [23][24] and phase variation[25][26]. Generally, rotation and displacement detection using microwave sensors is proposed for solid materials using stators and rotators where the sample is rotated in the sensing area with a certain dynamic range[27]–[29]. However, this creates friction between the sample and the sensor which has the potential to damage the surface of the sensor. In addition, the sample is placed on an open surface, so it is greatly influenced by changes in temperature and environment. Another constraint, the proposed sensor from previous work only has one single function so it cannot be used for displacement and rotation detection separately. In addition, sensors for displacement and rotation detection are only proposed for solid materials and are not supported for detection in liquid samples. Therefore, microwave sensors that have the capability to detect displacement and rotation of liquid samples are needed. Moreover, liquid displacement sensors are very useful for several applications, including biomedical and robotics [30], health monitoring and mobile healthcare[31]. This work provides an excellent solution by proposing a microwave sensor that has dual functional characteristics for displacement and angular detection for liquid samples. Furthermore, to maintain and control the influence of temperature and environment, the sample is contained in a polystyrene-mm pipe channel[32]–[34]. Moreover, polystyrene-mm pipe is proposed to reduce friction between the sensor and the sample so that the sensor surface is more durable and protected. Displacement and angular detection are determined based on the shift in the resonant frequency of the resonator. The main contribution of this work is to produce a dual functional microwave sensor that has the capability for displacement and angular detection in liquid samples in polystyrene-mm pipe channels. The proposed sensor has been successfully simulated and validated through the measurement process. Based on the measurement results, the proposed sensor has the ability to detect liquid displacement with a distance range of 1 - 4 cm and for angular detection with an angle range of 0 - 90°.

II. WORKING PRINCIPLE OF PROPOSED SENSOR

This section explains in detail the development model, structure of the ELC resonator and the sample placement scenario of the proposed sensor.

A. STRUCTURE OF ELC RESONATOR

The proposed microwave sensor based on ELC resonator uses RO4003C with permittivity of 3.55, tan δ of 0.0027 and thickness of 0.587 mm. The proposed resonator operates at a resonant frequency of f_r = 2.69 GHz with two ports representing *P1* and *P2*. The structure of the proposed sensor is shown in **Fig. 1(a)** while the concentration of the electric field and magnetic field is shown in **Fig. 1(b)** and **Fig 1(c).** The structure of the ELC resonator consists of the left and right inductive arms, while the capacitive area is in the gap between the strips in the middle of the resonator. The overall dimension of ELC resonator is shown in **Table 1**. Based on the simulation results using HFSS 15.0, the highest electric field concentration at f_r = 2.69 GHz is in the arms and gaps between the strips of the ELC resonator as shown in **Fig.1 (b)**, while the magnetic field concentration vanishes as shown in **Fig.1 (c)**.

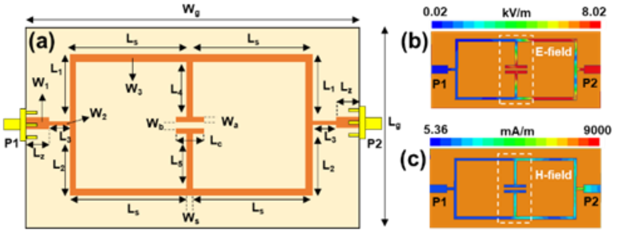

FIGURE 1. **(a) Structure of Electric field coupled resonator, (b) E-field at f_r = 2.69 GHz, (c) H-field at f_r = 2.69 GHz**

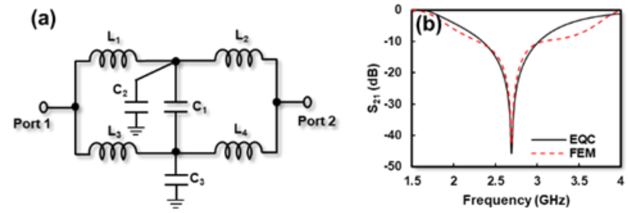

FIGURE 2. **(a) Equivalent circuit of electric field coupled resonator, (b) comparison of EQC and FEM of electric field coupled resonator**

Based on perturbation theory, the area of the resonator with a high electric field can be used to detect the characteristics of the sample[35].

Furthermore, the equivalent circuit of the ELC resonator can be derived based on *L* and *C* model as shown in **Fig.2 (a)**. The arm of the resonator is represented as an inductor while the gap between strip is represented as a capacitor. The values of *L* and *C* are extracted using AWR 2009 where $L_1 = L_2 = L_3 = L_4$ = 8.23 nH, C_1 = 0.17 pF and C_2 = 0.99 pF and C_3 = 1.25 pF which are connected to port 1 and port 2 with an impedance of 50 Ω. Therefore, the resonant frequency (f_r) of resonator can be determined using following Eq. (1)[36]:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \qquad (1)$$

A comparison of the simulation results from EQC and FEM is shown in **Fig. 2 (b)** where the results are both in line and operating at f_r = 2.69 GHz.

TABLE I
DIMENSION OF PROPOSED ELC RESONATOR

Parameter	Value (mm)	Parameter	Value (mm)
W_g	70	L_4	9
L_g	30	L_5	9
L_s	24.5	L_c	9
L_1	11	L_z	7
L_2	11	W_a	1
L_3	3	W_b	1
W_1	3	W_2, W_3	1

B. DEVELOPMENT MODEL OF ELC RESONATOR

The ELC resonator was developed in two steps where the proposed characteristic is a band stop response. The model

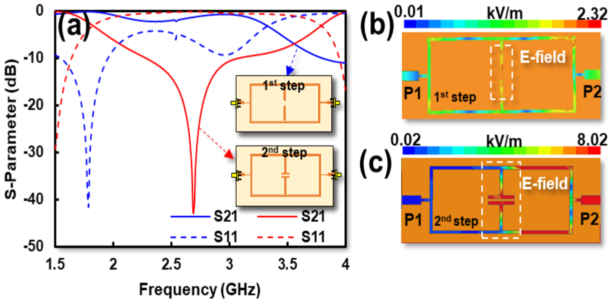

FIGURE 3. Development model of ELC resonator; (a) response of S-parameters, (b) E-field concentrations of ELC resonator at 1st and 2nd step

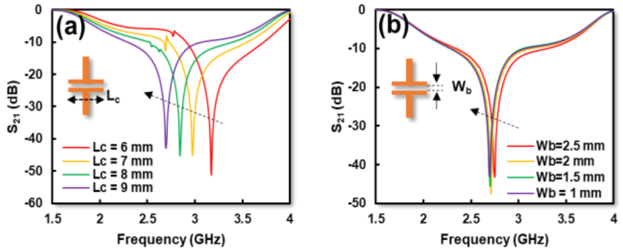

FIGURE 4. Iteration process; (a) iteration of L_c, (b) iteration of W_b

development of the ELC resonator is shown in **Fig. 3 (a)**, **Fig. 3 (b)** and **Fig. 3 (c)**.

The characteristics of the S-parameters at the 1st step show that the resonator has a band pass response where $S_{11} \leq$ -10 dB while $S_{21} \geq$ -10 dB in the frequency range of 1.5 - 3.2 GHz as shown by the red line in **Fig. 3 (a)**. Furthermore, for the 2nd step, the characteristics of the S-parameters show the band stop response where $S_{11} \geq$ -10 dB while $S_{21} \leq$ -10 dB in the frequency range of 1.7 GHz - 3.82 GHz as shown by the blue line in **Fig.3 (a)**. In addition, the characteristics of the electric field of the resonator for the 1st and 2nd steps are also observed as shown in **Fig.3 (b)** and **Fig. 3(c)**. The electric field concentration is observed at f_r = 2.69 GHz where for the 1st step the electric field is concentrated in the center of the ELC resonator while for the 2nd step it is in the gap between the strips of the ELC resonator.

Next, several iterations are carried out to control the resonant frequency and S_{21} of the resonator as shown in **Fig. 4 (a)** and **Fig. 4 (b)**. **Fig. 4 (a)** shows that the iteration of L_c causes the resonance frequency to shift lower in line with increasing length of L_c. In addition, the gap between the strips of the ELC resonator represented by W_b also has an impact on the resonant frequency and S_{21} of the resonator. Increasing the gap width W_b causes the resonant frequency of the resonator to shift towards high. This finding shows that the gap in the strip is an area that has high sensitivity so it can be recommended as a sensing area for placing samples.

C. FABRICATION OF PROPOSED RESONATOR

The fabrication results of the front and back side of the resonator are shown in **Fig.5 (a)** and **Fig. 5 (b)** where the ELC resonator is in the front layer and the ground plane is in the back layer. The ELC resonator is connected to port 1 and port 2 and has the characteristics of a Band Stop Filter (BSF). Moreover, the comparison of simulation and measurement results from the resonator is shown in **Fig. 5 (c)**.

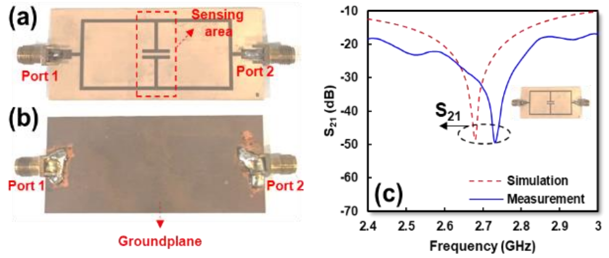

FIGURE 5. (a) Fabrication of ELC resonator at the front side, (b) fabrication of ELC resonator at the back side, (c) simulation and measurement of proposed resonator

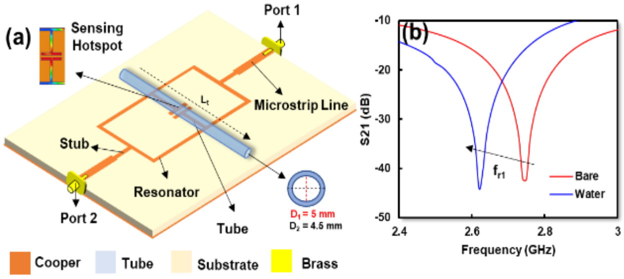

FIGURE 6. (a) Scenario placement of sample, (b) simulation of bare and with water condition.

Based on the measurement results, there is a slight difference between measurement and simulation result where the resonance frequency shifts from 2.69 GHz to 2.72 GHz. This is due to errors from the fabrication process and the permittivity of RO4003C which is in the range 3.38 - 3.55 [37][38].

D. SCENARIO OF SAMPLE PLACEMENT

The sample placement scenario is determined based on the location of the resonator with the highest electric field as shown in **Fig.6 (a).** In this paper, the sample is placed in the center of the ELC resonator using a polystyrene-mm pipe channel based on polystyrene-mm pipe channel [17] with a permittivity of 3.1 and a diameter represented by D_1 and D_2 of 5 mm and 4.5 mm and length of polystyrene-mm pipe channel represented by L_t of 40 mm, respectively. The sample placement scenario consists of two conditions, including the bare condition where the polystyrene-mm pipe channel is filled with air samples and the other condition is when the polystyrene-mm pipe channel is filled with water samples. The polystyrene-mm pipe channel is placed in line with the sensing area of the ELC resonator which is located in the middle arm and the gap of the resonator.

The simulation results from bare conditions and with water samples shown in **Fig. 6 (b)** show that the resonance frequency of the resonator moves to the lower frequency from 2.75 GHz to 2.62 GHz because the permittivity of water

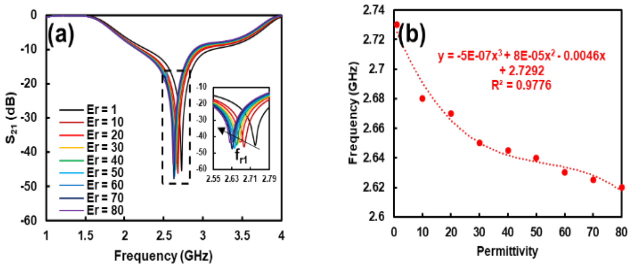

FIGURE 7. **(a) Simulation with range ε_r of 1 – 80, (b) correlation between frequency and permittivity range ε_r of 1 – 80**

is higher than bare where the permittivity of water is ε_r = 80 and bare is ε_r = 1. Furthermore, to demonstrate the performance of the proposed sensor, the permittivity of the sample inside the polystyrene-mm pipe channel is changed to a permittivity range of ε_r = 1 - 80. Based on **Fig.7 (a)**, the resonant frequency of the resonator shifts from 2.73 GHz to 2.62 GHz with a permittivity range of 1 – 80 with ΔF of 0.11 GHz.

It should be noted, based on the simulation results from **Fig. 7 (a)** and **Fig.7 (b)**, it shows that changes in the permittivity of the sample in the polystyrene-mm pipe channel greatly affect the resonant frequency of the resonator where the resonant frequency moves to a lower frequency in line with an increase in the permittivity of the sample.

III. MEASUREMENT RESULT AND VERIFICATION

In this chapter, the measurement process and scenarios for liquid displacement and angular detection are explained in detail. The measurement process was carried out in the laboratory using a Vector Network Analyzer (VNA) with a frequency range of 2 - 3 GHz, a frequency step size of 0.01 GHz and an ambient temperature of 25°C.

A. SCENARIO FOR LIQUID DISPLACEMENT DETECTION

The proposed resonator consisting of port 1 and port 2 is connected to the vector analyzer using a coaxial cable with an impedance of 50Ω where the sensor and sample are placed using a holder as shown in **Fig 8 (a)**. Liquid displacement detection is proposed by placing a stopper in the center of the sample in a polystyrene-mm pipe channel filled with water content as shown in **Fig.8 (b)**.

It should be noted, the sample in the plastic tube [17] placed carefully and is in direct contact with the sensing area in the middle of the ELC resonator. The stopper is placed in the middle of the polystyrene-mm pipe channel so that the water sample inside is clogged. Additionally, the area of the clogged polystyrene-mm pipe channel is filled with air samples represented by bare. The sample in the polystyrene-mm pipe channel will be moved vertically using a holder with a distance d of 1 - 4 cm as shown in **Fig.8 (c)**. Furthermore, liquid displacement detection is determined by observing the shift in the resonance frequency when the sample moves through the sensing area of the resonator.

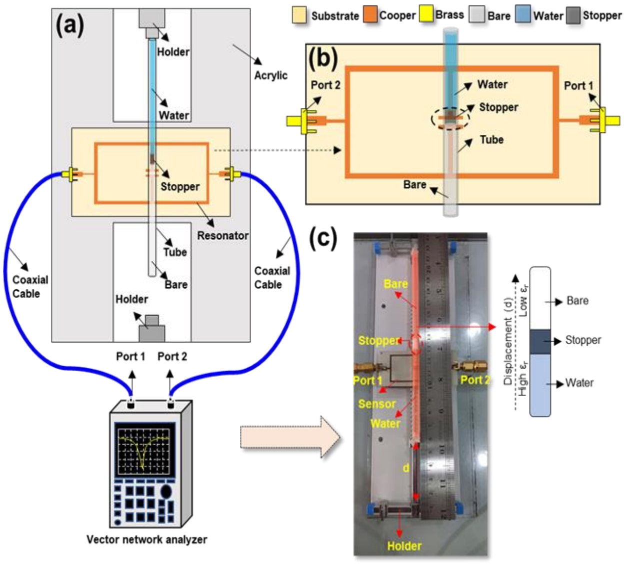

FIGURE 8. **(a) Scenario for liquid displacement detection, (b) detail structure of liquid displacement detection, (c) measurement setup for liquid displacement detection using proposed sensor.**

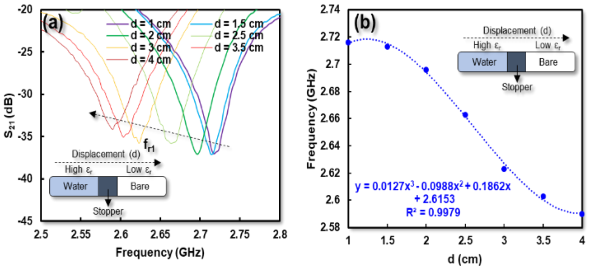

FIGURE 9. **(a) Measurement result of liquid displacement detection with d = 1 – 4 cm, (b) correlation between resonant frequency and liquid displacement with d = 1 – 4 cm.**

Based on the measurement results, the resonant frequency of the resonator shifts from 2.716 GHz to 2.59 GHz with ΔF of 0.126 GHz in line with the sample displacement in the polystyrene-mm pipe channel which is clogged by a stopper with a distance range of d = 1 - 4 cm as shown in **Fig.8 (a)** and **Fig.8 (b)**. This finding shows that the proposed sensor has interacted with the sample to detect the displacement of the sample. The resonant frequency of the resonator shifts to low frequencies slowly in line with the displacement of the sample. This occurs because there is a change in the permittivity of the sample, where the water sample has a higher permittivity than the bare air sample, so it greatly influences the resonance frequency of the resonator. Furthermore, displacement detection with the proposed resonator can be determined based on **Eq. (2)**[7]:

$$f_{r\,(c)} = 0.01273\, d^3 - 0.988\, d^2 + 0.1862\, d - 2.6153 \quad (2)$$

where $f_{r\,(b)}$ is the resonant frequency of the resonator for displacement detection and d represents the distance of the displacement in the water-filled polystyrene-mm pipe channel.

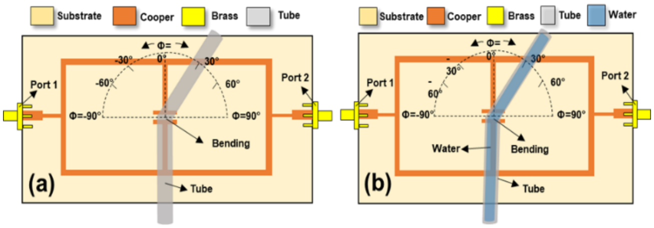

FIGURE 10. **Scenario of angular detection from 0° - 90°; (a) without water, (b) with water.**

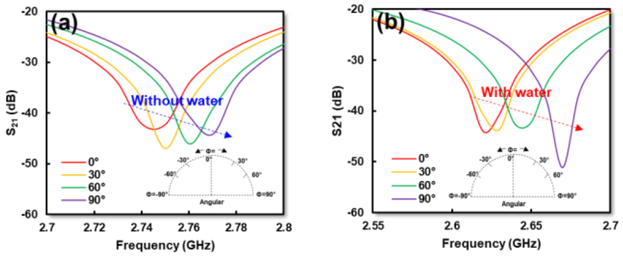

FIGURE 11. **Simulation result of angular detection from 0° - 90°; (a) without water, (b) with water**

Moreover, the sensitivity *(S)* of the sensor is determined based on the following **Eq. (3)**[21]:

$$S = \frac{\Delta F\ (GHz)}{\Delta d\ (cm)} \tag{3}$$

where ΔF represents the shift in the resonant frequency of the resonator and Δd represents the displacement of the sample in the polystyrene-mm pipe channel. Based on **Eq. (3)**, the sensitivity of the sensor for displacement detection is 31.5 MHz/cm with a range d of 1 - 4 cm.

B. SCENARIO FOR LIQUID ANGULAR DETECTION

Furthermore, liquid angular detection is proposed by rotating the sample inside the polystyrene-mm pipe channel with an angle range of 0° - 90°. In this paper, the rotation of the sample in the polystyrene-mm pipe channel is divided into two conditions, including with water and without water as shown in **Fig. 10 (a)** and **Fig.10 (b).** The sample in the polystyrene-mm pipe channel is rotated clockwise at angles of 0°, 30°, 60° and 90°.

The simulation results in **Fig.11 (a)** and **Fig.11 (b)** show that the resonant frequency of the resonator shifts to a higher frequency in line with increasing the rotation angle of the sample for conditions without water and with water content. The resonant frequency shifts from 2.74 GHz to 2.77 GHz in conditions without water, while for conditions with water it shifts from 2.62 GHz to 2.67 GHz with an angle range of 0° - 90° as shown in **Fig. 12 (a)** and **Fig. 12 (b)**.

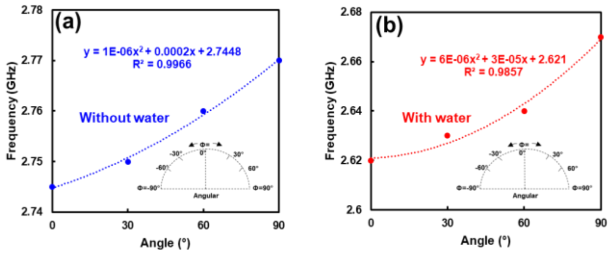

FIGURE 12. **Simulation result of correlation between resonant frequency and angle from 0° - 90°; (a) without water, (b) with water**

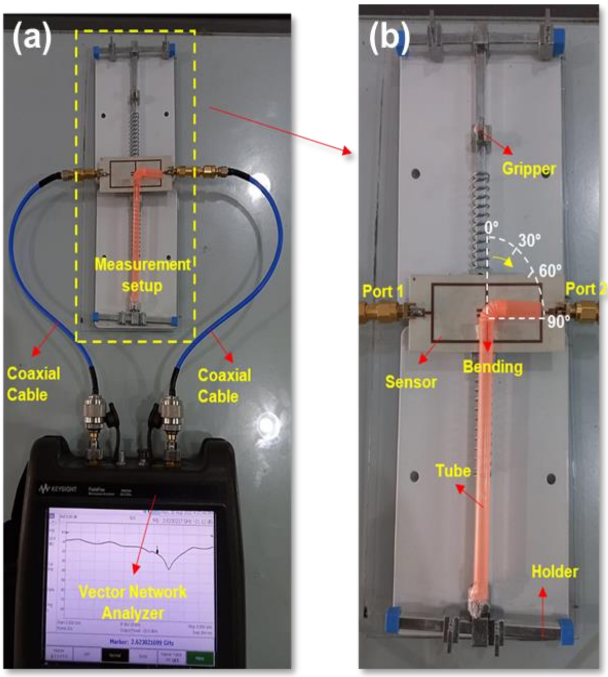

FIGURE 13. **(a) Measurement setup with VNA, (b) Measurement scenario for angular detection from 0° - 90°**

Furthermore, validation of angular detection is carried out by measuring the process using a VNA connected to port 1 and port 2 of the resonator placed in the holder using a coaxial cable with an impedance of 50 Ω. The sample in the polystyrene-mm pipe channel is carefully placed in the sensing area which is located in the middle of the ELC resonator as shown in **Fig.13 (a)** and **Fig.13 (b)**.

Moreover, to ensure that the sample position is constant and stable, a gripper is proposed in the measurement setup to lock the position of the sample and sensor. The measurement results of angular detection when the polystyrene-mm pipe channel is filled with water and without water are shown in **Fig.14 (a)** and **Fig.14 (b).**

Based on the measurement results, the frequency of the resonator shifts from 2.716 GHz to 2.723 GHz when the polystyrene-mm pipe channel is without water, whereas when the polystyrene-mm pipe channel is filled with water, the frequency shifts from 2.675 GHz to 2.705 GHz with an angle range of 0° - 90° as shown in **Fig.15 (a)** and **Fig.15 (b)**. These findings indicate that the proposed sensor interacts with the sample so that the resonant frequency of the resonator changes in line with an increase in the rotation angle of the sample in the polystyrene-mm pipe channel.

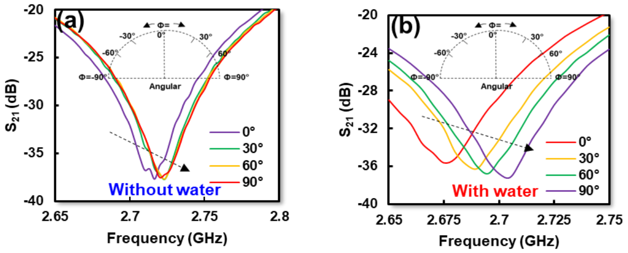

FIGURE 14. Measurement result of angular detection from 0° - 90°; (a) without water, (b) with water

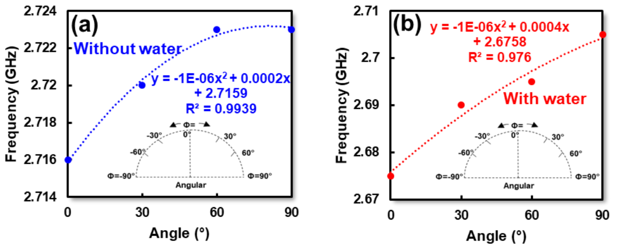

FIGURE 15. Measurement result of correlation between resonant frequency and angular from 0° - 90°; (a) without water, (b) with water

It should be noted, the resonance frequency shifts to a higher frequency due to the interaction of the sample and sensor which changes while the sample inside polystyrene-mm pipe channel shifts away from the surface of the sensing area with water content to bare condition (without sample). In other words, the permittivity of the sample changes from higher to lower. This condition changes the concentration of the electric field of the resonator and greatly influences the resonant frequency of the resonator.

Furthermore, angular detection of polystyrene-mm pipe channel without and with water can be determined based on the following **Eq. (4)** and **Eq. (5)**:

$$f_{r\,(ba)} = -0.000001\,x^2 - 0.0002\,x + 2.7159 \qquad (4)$$

$$f_{r\,(bw)} = -0.000001\,x^2 - 0.0004\,x + 2.6578 \qquad (5)$$

where $f_{r\ (ba)}$ and $f_{r\ (bw)}$ is the resonant frequency of the resonator for angular detection with and without water and x represents the angle of the angular in the water-filled polystyrene-mm pipe channel.

Moreover, the sensitivity (S) of the sensor is determined based on the following **Eq. (6)**[18]:

$$S = \frac{\Delta F\ (GHz)}{\Delta\theta\ (°)} \qquad (6)$$

where ΔF represents the shift in the resonant frequency of the resonator and $\Delta\theta$ represents the rotation of the sample in the polystyrene-mm pipe channel.

Based on **Eq. (6)**, the sensitivity of the sensor for angular detection of polystyrene-mm pipe channel without and with water content are 0.07 MHz/^{o} and 0.33 MHz/^{o} with a dynamic range of 0 - 90°. Moreover, average and deviation of repeatability measurements with 3 cycles are proposed to show the error bars of angular detection for sample filled in polystyrene-mm pipe channel with and without water using the proposed sensor as shown in **Fig.16.**

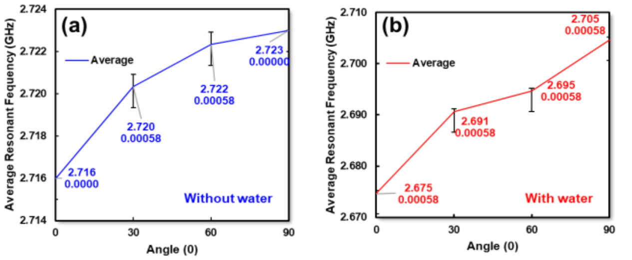

FIGURE 16. Average and deviation from repeatability measurement for angular detection; (a) without water, (b) with water.

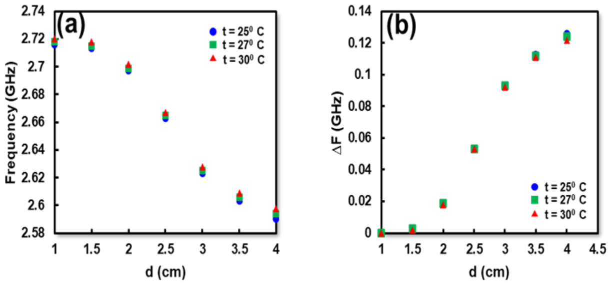

FIGURE 17. Displacement detection of liquid samples based on different temperatures; (a) response of the resonant frequency, (b) ΔF of proposed sensor.

Based on **Fig.16 (a)** and **Fig. 16 (b)**, the deviation from the repeatability measurement results is in the range 0 - 0.00058 for angular detection with and without water. These findings indicate that the proposed sensor has a low error bar for angular detection in samples with and without water. To show the effect of changing the temperature of the liquid sample on displacement detection, validation with measurements at three different temperatures is proposed as shown in **Fig. 17 (a)** and **Fig. 17 (b)**.

Referring to **Fig.17 (a)**, changes in temperature in the sample have an impact on shifting the resonant frequency of the resonator towards high frequencies correlated with previous work [34] [39]. The maximum ΔF of the proposed sensor for three different temperatures are 0.126 GHz, 0.124 GHz and 0.122 GHz respectively as shown in **Fig. 17 (b)**. The sensitivity of the sensor based on temperature changes is 31.5 MHz/cm, 31 MHz/cm and 30.5 MHz/cm respectively. These findings indicate that changing the temperature of the sample has an impact on the shift in the resonance frequency and sensitivity of the sensor but is not significant. Therefore, the temperature of the sample must be verified before the measurement process is carried out to obtain optimal performance.

IV. VALIDATION WITH PREVIOUS WORK

To validate the performance of the proposed sensor, a comprehensive evaluation with previous work is proposed as shown in **Table 2**. Based on previous work, the detection of linear and angular displacement of samples using microwave

TABLE II
COMPARISON OF PROPOSED SENSOR BASED ON DISPLACEMENT / ROTATION TECHNIQUE WITH EXISTING WORKS

Ref	Method	Freq (GHz)	Sensing mechanism	Sample	Dynamic Range		Sensitivity Average		Polystyrene mm-pipe	Sensor Type		Dual Functional
					Displacement	Angular	Displacement	Angular		Displacement	Angular	
[1]	Step impedance transmission lines	2.00	Phase variation	Solid	0 – 40 mm	-	312.7°/ mm	-	-	Yes	-	-
[3]	H-shaped resonator	4.80 2.59	Freq shift	Solid	0 – 12 mm	-	147.8 MHz/mm	-	-	Yes	-	-
[7]	Dielectric resonator	3.70	Notch depth	Solid	1 – 10 mm	-	0.095 dB/ mm	-	-	Yes	-	-
[19]	Transversal signal interference	0.92	Freq shift	Solid	-	0 – 180˚	-	3.15 MHz /˚	-	-	Yes	-
[21]	CSRR	5.80	Freq shift	Solid	-	0 – 90˚	-	2.37 MHz/˚	-	-	Yes	-
[23]	Transmission line	1.21	Notch depth	Solid	-	0 – 90˚	-	0.095 dB/˚	-	-	Yes	-
[27]	TFS - coupled slot line	2.17	Freq shift	Solid	-	0 – 90˚	-	2.27 MHz/˚	-	-	Yes	-
[28]	U-shaped resonator	1.20	Freq shift	Solid	-	0 – 180˚	-	1.94 MHz/˚	-	-	Yes	-
[32]	Stepped impedance Transmission lines	2.00	Phase variation	Solid	0 – 3 mm	-	528.7˚/ mm	-	-	Yes	-	-
This work	**ELC Resonator**	**2.72**	**Freq shift**	**Liquid**	**1 – 4 cm**	**0 – 90˚**	**31.5 MHz/cm**	**0.33 MHz/˚**	**Yes**	**Yes**	**Yes**	**Yes**

sensors are divided into three types of mechanisms based on frequency shift, phase variation and notch depth.

Previous work [1][32] proposed a microwave sensor based on transmission line for displacement detection of solid materials with a maximum dynamic range of 3 - 40 mm and maximum sensitivity of 312.7°/ mm and 528.7˚/ mm where the displacement detection was determined based on phase variations. However, the sensor only has one function for displacement detection and cannot be used for angular displacement of materials. Other works [7] [23] proposed a microwave sensor for displacement and rotation detection of solid materials based on notch depth with a maximum dynamic range of 10 mm and 90˚. Nevertheless, the proposed sensor only supports displacement detection in solid materials so it cannot be used for liquid materials. Furthermore, detection of linear displacement of solid materials based on resonant frequency shifts has been described in [3] where the maximum dynamic range is 12 mm with a sensitivity of 147.8 MHz/mm. Rotation detection of solid materials based on frequency shift has also been described in [19][21][23][28] where the solid material is moved using a rotator and the sensor is placed on the stator. However, high friction between the material and the sensor has the potential to damage the surface of the resonator and will reduce the performance of the sensor.

Furthermore, a comprehensive comparison of types, sensing parameters and proposed applications of displacement and rotation sensors is shown in **Table 3**. Previous work [3][19][21][23] proposed a band stop filter for displacement and rotation detection which is recommended for industrial applications including flow detection in liquids, space vehicle and rotation detection in AC motors. In addition, other work [7][23][27][32] proposed a band stop filter for displacement/rotation detection which is recommended for industrial, biomedical and energy applications while previous work [1], proposed a single port resonator for motor rotation detection AC based on phase variations.

TABLE III
COMPARISON OF TYPE, SENSING PARAMETERS AND PROSPECTIVE APPLICATIONS OF DISPLACEMENT / ROTATION SENSORS

Ref	Type of resonator	Sensing parameter	Prospective applications
[1]	Single port resonator	Phase	Industrial
[3]	Band stop filter	S_{21}	Industrial
[7]	Band pass filter	S_{21}	Industrial
[19]	Band stop filter	S_{21}	Industrial
[21]	Band stop filter	S_{21}	Space vehicle (satellites)
[23]	Band pass filter	Phase	Industrial
[27]	Band pass filter	S_{21}	Industrial
[28]	Band stop filter	S_{21}	Industrial
[32]	Band pass filter	S_{21}	Biomedical and energy
This work	Band stop filter	S_{21}	Industrial and Biomedical

Therefore, this work makes a significant contribution by proposing a dual functional microwave sensor for translation and angular detection in liquid samples using polystyrene-mm pipe channels. The proposed sensor has the capability to detect displacement and angular detection separately based on the frequency shift of the resonator. Polystyrene-mm pipe channels are proposed to reduce the friction between the sensor and the sample and maintain the temperature of the sample in order to obtain high-precision measurements. The proposed sensor has excellent performance with a maximum sensitivity of 31.5 MHz/cm for liquid displacement with a range of d = 1 - 4 cm and 0.33 MHz/° for angular detection with an angle range of 0 – 90°.

V. CONCLUSION

A microwave sensor with dual functional characteristics for liquid displacement and angular detection in polystyrene-mm pipe channel has been proposed and presented comprehensively in this paper. The proposed sensor is based on an ELC resonator operating at a resonant frequency of 2.72 GHz. The sample used is liquid material contained in a polystyrene-mm pipe channel. Displacement and angular detection are determined based on the shift in the resonant frequency of the resonator. Based on the measurement results, the proposed sensor has a sensitivity of 31.5 MHz/cm with a displacement range of 1 - 4 cm and 0.33 GHz /° with an angle range of 0 - 90°. This paper makes a significant contribution by proposed a dual functional microwave sensor for displacement and angular detection that can be recommended for the automotive, robotics and aerospace industries.

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Decision letter (Revision 1)

Dual Functional Liquid Displacement and Angular Detection Based on Band Stop Response Microwave Sensor

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Syah Alam *et al.*
Department of Electrical Engineering, Universitas Trisakti, West Jakarta 11440, Indonesia
Email: syah.alam@trisakti.ac.id

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Correction:

[6] J. Ma, Y. Chen, and J. Huang, "A Microwave Displacement Sensor Based on SIW Double Reentrant Cavity with Ring Gaps," *Prog. Electromagn. Res. M*, vol. 113, no.1, September, pp. 35–45, 2022, doi: 10.2528/PIERM22050102.

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[20] M. H. Zarifi and M. Daneshmand, "Wide dynamic range microwave planar coupled ring resonator for sensing applications," *Appl. Phys. Lett.*, vol. 108, no. 23, 2016, pp. 1-4, doi: 10.1063/1.4953465.

[30] G. Keulemans, F. Ceyssens, and R. Puers, "An ionic liquid based strain sensor for large displacement measurement," *Biomed. Microdevices*, vol. 19, no. 1, 2017, pp. 1-9, doi: 10.1007/s10544-016-0141-4.

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[20] M. H. Zarifi and M. Daneshmand, "Wide dynamic range microwave planar coupled ring resonator

for sensing applications," *Appl. Phys. Lett.*, vol. 108, no. 23, 2016, pp. 1-4, doi: 10.1063/1.4953465.

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[37] S. Kiani, P. Rezaei, and M. Fakhr, "Real-Time Measurement of Liquid Permittivity Through Label-Free Meandered Microwave Sensor," *IETE Journal of Research*, pp. 1–11, Jul. 2023, doi: 10.1080/03772063.2023.2231875.

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Published Paper

RESEARCH ARTICLE

Dual Functional Liquid Displacement and Angular Detection Based on Band Stop Response Microwave Sensor

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This work was supported by Ministry of Education and Culture, Republic of Indonesia, Institute for Research and Community Service Universitas Trisakti. The author extends their appreciation to Universiti Teknikal Malaysia Melaka (UTeM) to support the study under grant Jurnal/2022/FTKEK/Q00086.

ABSTRACT This paper proposes dual functional microwave sensor for displacement and angular detection of liquid material based on electric coupled (ELC) resonator. The proposed resonator uses a two-port band stop filter operating at a resonant frequency of 2.72 GHz. Polystyrene-mm pipe channels are used to accommodate water samples placed in the sensing area of the sensor in the center of the ELC resonator. Displacement and angular detection were observed based on the shift in the resonant frequency of the resonator. Based on the measurement results, the proposed sensor has a sensitivity for displacement detection of 31.5 MHz/cm with a distance range of d = 1 – 4 cm while for angular detection it is 0.33 MHz/° with a rotation angle of 0 – 90° for polystyrene-mm pipe channel filled with water content. This paper makes a significant contribution by proposed a dual functional microwave sensor for displacement and angular detection that can be recommended for the automotive, robotics and aerospace industries.

INDEX TERMS Dual functional, displacement, angular, polystyrene-mm pipe, microwave sensor.

I. INTRODUCTION

Displacement sensors play an important role for several industries that require high precision such as the automotive, robotics and aerospace industries [1], [2], [3], [4]. Generally, displacement sensors consist of two types, including linear and angular displacement. Linear displacement is determined based on distance while angular displacement is based on the angle between the sensor and the sample [5], [6]. One of the strategies for detecting sample displacement is to utilize a microwave sensor [7], [8], [9], [10]. Microwave sensors have advantages including compact design, low cost and high accuracy. Microwave sensors have been widely developed to detect the characteristics of solid materials [11], [12], [13], liquids [14], [15], [16], [17] and displacement [18], [19], [20]. Several previous works proposed sensors for linear and angular displacement detection in solid materials using microwave sensors with a certain dynamic range based on frequency shift [21], [22], notch depth [23], [24] and phase variation [25], [26]. Generally, rotation and displacement detection using microwave sensors is proposed for solid materials using stators and rotators where the sample is rotated in the

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sensing area with a certain dynamic range [27], [28], [29]. However, this creates friction between the sample and the sensor which has the potential to damage the surface of the sensor. In addition, the sample is placed on an open surface, so it is greatly influenced by changes in temperature and environment. Another constraint, the proposed sensor from previous work only has one single function so it cannot be used for displacement and rotation detection separately. In addition, sensors for displacement and rotation detection are only proposed for solid materials and are not supported for detection in liquid samples. Therefore, microwave sensors that have the capability to detect displacement and rotation of liquid samples are needed. Moreover, liquid displacement sensors are very useful for several applications, including biomedical and robotics [30], health monitoring and mobile healthcare [31]. This work provides an excellent solution by proposing a microwave sensor that has dual functional characteristics for displacement and angular detection for liquid samples. Furthermore, to maintain and control the influence of temperature and environment, the sample is contained in a polystyrene-mm pipe channel [32], [33], [34]. Moreover, polystyrene-mm pipe is proposed to reduce friction between the sensor and the sample so that the sensor surface is more durable and protected. Displacement and angular detection are determined based on the shift in the resonant frequency of the resonator. The main contribution of this work is to produce a dual functional microwave sensor that has the capability for displacement and angular detection in liquid samples in polystyrene-mm pipe channels. The proposed sensor has been successfully simulated and validated through the measurement process. Based on the measurement results, the proposed sensor has the ability to detect liquid displacement with a distance range of 1 - 4 cm and for angular detection with an angle range of 0 - 90°.

II. WORKING PRINCIPLE OF PROPOSED SENSOR

This section explains in detail the development model, structure of the ELC resonator and the sample placement scenario of the proposed sensor.

A. STRUCTURE OF ELC RESONATOR

The proposed microwave sensor based on ELC resonator uses RO4003C with permittivity of 3.55, tan δ of 0.0027 and thickness of 0.587 mm. The proposed resonator operates at a resonant frequency of $f_r = 2.69$ GHz with two ports representing *P1* and *P2*. The structure of the proposed sensor is shown in **Fig. 1(a)** while the concentration of the electric field and magnetic field is shown in **Fig. 1(b)** and **Fig 1(c)**. The structure of the ELC resonator consists of the left and right inductive arms, while the capacitive area is in the gap between the strips in the middle of the resonator. The overall dimension of ELC resonator is shown in **Table 1**. Based on the simulation results using HFSS 15.0, the highest electric field concentration at $f_r = 2.69$ GHz is in the arms and gaps between the strips of the ELC resonator as shown in **Fig.1 (b)**, while the magnetic field concentration vanishes as shown in **Fig.1 (c)**.

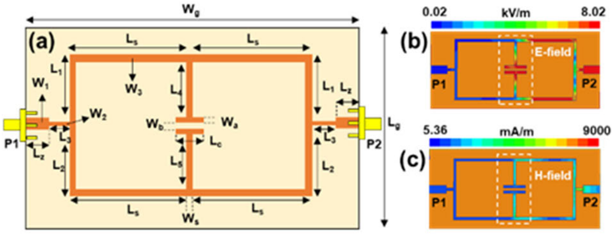

FIGURE 1. (a) Structure of electric field coupled resonator, (b) E-field at $f_r = 2.69$ GHz, (c) H-field at $f_r = 2.69$ GHz.

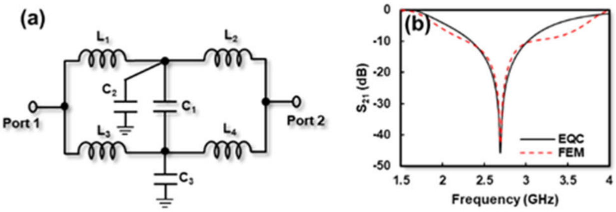

FIGURE 2. (a) Equivalent circuit of electric field coupled resonator, (b) comparison of EQC and FEM of electric field coupled resonator.

TABLE 1. Dimension of proposed ELC resonator.

Parameter	Value (mm)	Parameter	Value (mm)
W_g	70	L_4	9
L_g	30	L_5	9
L_s	24.5	L_c	9
L_1	11	L_z	7
L_2	11	W_a	1
L_3	3	W_b	1
W_1	3	W_2, W_3	1

Based on perturbation theory, the area of the resonator with a high electric field can be used to detect the characteristics of the sample [35].

Furthermore, the equivalent circuit of the ELC resonator can be derived based on *L* and *C* model as shown in **Fig.2 (a)**. The arm of the resonator is represented as an inductor while the gap between strip is represented as a capacitor. The values of *L* and *C* are extracted using AWR 2009 where $L_1 = L_2 = L_3 = L_4 = 8.23$ nH, $C_1 = 0.17$ pF and $C_2 = 0.99$ pF and $C_3 = 1.25$ pF which are connected to port 1 and port 2 with an impedance of 50 Ω. Therefore, the resonant frequency (f_r) of resonator can be determined using following Eq. (1) [36]:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

A comparison of the simulation results from EQC and FEM is shown in **Fig. 2 (b)** where the results are both in line and operating at $f_r = 2.69$ GHz.

B. DEVELOPMENT MODEL OF ELC RESONATOR

The ELC resonator was developed in two steps where the proposed characteristic is a band stop response. The model

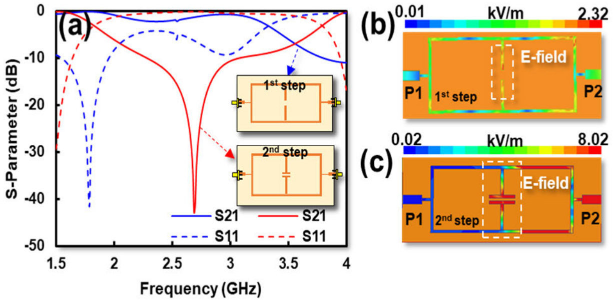

FIGURE 3. Development model of ELC resonator; (a) response of S-parameters, (b) E-field concentrations of ELC resonator at 1st and 2nd step.

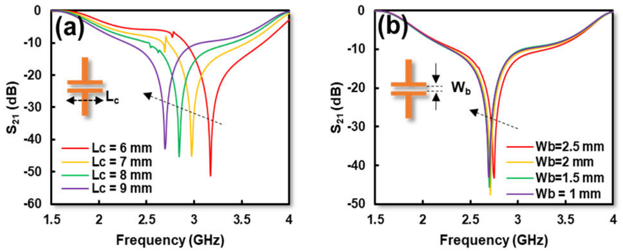

FIGURE 4. Iteration process; (a) iteration of L_c, (b) iteration of W_b.

development of the ELC resonator is shown in **Fig. 3 (a)**, **Fig. 3 (b)** and **Fig. 3 (c)**.

The characteristics of the S-parameters at the 1st step show that the resonator has a band pass response where $S_{11} \leq -10$ dB while $S_{21} \geq -10$ dB in the frequency range of 1.5 - 3.2 GHz as shown by the red line in **Fig. 3 (a)**. Furthermore, for the 2nd step, the characteristics of the S-parameters show the band stop response where $S_{11} \geq -10$ dB while $S_{21} \leq -10$ dB in the frequency range of 1.7 GHz - 3.82 GHz as shown by the blue line in **Fig.3 (a)**. In addition, the characteristics of the electric field of the resonator for the 1st and 2nd steps are also observed as shown in **Fig.3 (b)** and **Fig. 3(c)**. The electric field concentration is observed at $f_r = 2.69$ GHz where for the 1st step the electric field is concentrated in the center of the ELC resonator while for the 2nd step it is in the gap between the strips of the ELC resonator.

Next, several iterations are carried out to control the resonant frequency and S_{21} of the resonator as shown in **Fig. 4 (a)** and **Fig. 4 (b)**. **Fig. 4 (a)** shows that the iteration of L_c causes the resonance frequency to shift lower in line with increasing length of L_c. In addition, the gap between the strips of the ELC resonator represented by W_b also has an impact on the resonant frequency and S_{21} of the resonator. Increasing the gap width W_b causes the resonant frequency of the resonator to shift towards high. This finding shows that the gap in the strip is an area that has high sensitivity so it can be recommended as a sensing area for placing samples.

C. FABRICATION OF PROPOSED RESONATOR

The fabrication results of the front and back side of the resonator are shown in **Fig. 5 (a)** and **Fig. 5 (b)** where the ELC resonator is in the front layer and the ground plane is in the back layer. The ELC resonator is connected to port 1 and port 2 and has the characteristics of a Band Stop Filter (BSF). Moreover, the comparison of simulation and measurement results from the resonator is shown in **Fig. 5 (c)**.

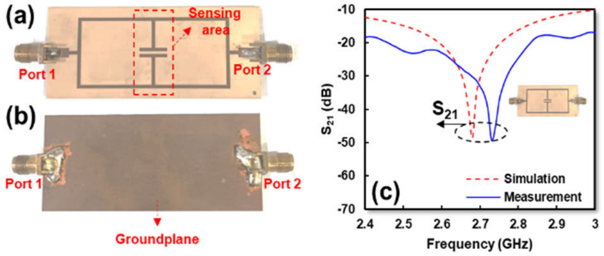

FIGURE 5. (a) Fabrication of ELC resonator at the front side, (b) fabrication of ELC resonator at the back side, (c) simulation and measurement of proposed resonator.

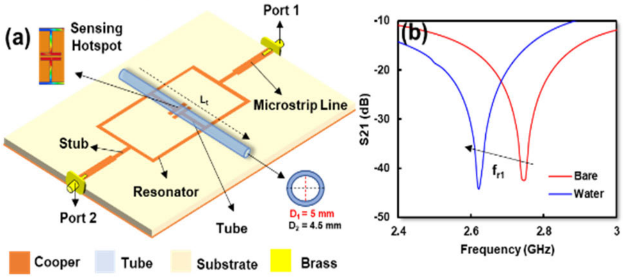

FIGURE 6. (a) Scenario placement of sample, (b) simulation of bare and with water condition.

Based on the measurement results, there is a slight difference between measurement and simulation result where the resonance frequency shifts from 2.69 GHz to 2.72 GHz. This is due to errors from the fabrication process and the permittivity of RO4003C which is in the range 3.38 - 3.55 [37], [38].

D. SCENARIO OF SAMPLE PLACEMENT

The sample placement scenario is determined based on the location of the resonator with the highest electric field as shown in **Fig.6 (a).** In this paper, the sample is placed in the center of the ELC resonator using a polystyrene-mm pipe channel based on polystyrene-mm pipe channel [17] with a permittivity of 3.1 and a diameter represented by D_1 and D_2 of 5 mm and 4.5 mm and length of polystyrene-mm pipe channel represented by L_t of 40 mm, respectively. The sample placement scenario consists of two conditions, including the bare condition where the polystyrene-mm pipe channel is filled with air samples and the other condition is when the polystyrene-mm pipe channel is filled with water samples. The polystyrene-mm pipe channel is placed in line with the sensing area of the ELC resonator which is located in the middle arm and the gap of the resonator.

The simulation results from bare conditions and with water samples shown in **Fig. 6 (b)** show that the resonance frequency of the resonator moves to the lower frequency from 2.75 GHz to 2.62 GHz because the permittivity of water is higher than bare where the permittivity of water is $\varepsilon_r = 80$ and bare is $\varepsilon_r = 1$. Furthermore, to demonstrate the performance

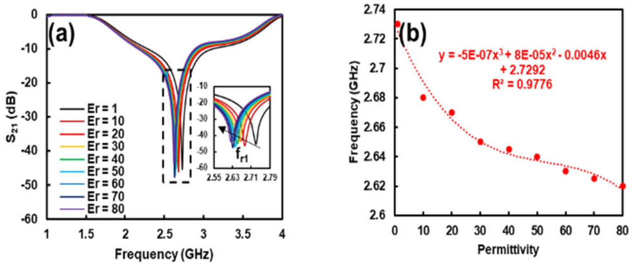

FIGURE 7. **(a) Simulation with range ε_r of 1 – 80, (b) correlation between frequency and permittivity range ε_r of 1 – 80.**

of the proposed sensor, the permittivity of the sample inside the polystyrene-mm pipe channel is changed to a permittivity range of $\varepsilon_r = 1$ - 80. Based on **Fig.7 (a)**, the resonant frequency of the resonator shifts from 2.73 GHz to 2.62 GHz with a permittivity range of 1 – 80 with ΔF of 0.11 GHz.

It should be noted, based on the simulation results from **Fig. 7 (a)** and **Fig.7 (b)**, it shows that changes in the permittivity of the sample in the polystyrene-mm pipe channel greatly affect the resonant frequency of the resonator where the resonant frequency moves to a lower frequency in line with an increase in the permittivity of the sample.

III. MEASUREMENT RESULT AND VERIFICATION

In this chapter, the measurement process and scenarios for liquid displacement and angular detection are explained in detail. The measurement process was carried out in the laboratory using a Vector Network Analyzer (VNA) with a frequency range of 2 - 3 GHz, a frequency step size of 0.01 GHz and an ambient temperature of 25° C.

A. SCENARIO FOR LIQUID DISPLACEMENT DETECTION

The proposed resonator consisting of port 1 and port 2 is connected to the vector analyzer using a coaxial cable with an impedance of 50Ω where the sensor and sample are placed using a holder as shown in **Fig 8(a)** . Liquid displacement detection is proposed by placing a stopper in the center of the sample in a polystyrene-mm pipe channel filled with water content as shown in **Fig. 8 (b)**.

It should be noted, the sample in the plastic tube [17] placed carefully and is in direct contact with the sensing area in the middle of the ELC resonator. The stopper is placed in the middle of the polystyrene-mm pipe channel so that the water sample inside is clogged. Additionally, the area of the clogged polystyrene-mm pipe channel is filled with air samples represented by bare. The sample in the polystyrene-mm pipe channel will be moved vertically using a holder with a distance d of 1 - 4 cm as shown in **Fig.8 (c)**. Furthermore, liquid displacement detection is determined by observing the shift in the resonance frequency when the sample moves through the sensing area of the resonator.

Based on the measurement results, the resonant frequency of the resonator shifts from 2.716 GHz to 2.59 GHz with ΔF of 0.126 GHz in line with the sample displacement in the polystyrene-mm pipe channel which is clogged by a stopper with a distance range of d = 1 - 4 cm as shown in **Fig.8 (a)** and **Fig.8 (b)**. This finding shows that the proposed sensor has interacted with the sample to detect the displacement of the sample. The resonant frequency of the resonator shifts to low frequencies slowly in line with the displacement of the sample. This occurs because there is a change in the permittivity of the sample, where the water sample has a higher permittivity than the bare air sample, so it greatly influences the resonance frequency of the resonator. Furthermore, displacement detection with the proposed resonator can be determined based on **Eq. (2)** [7]:

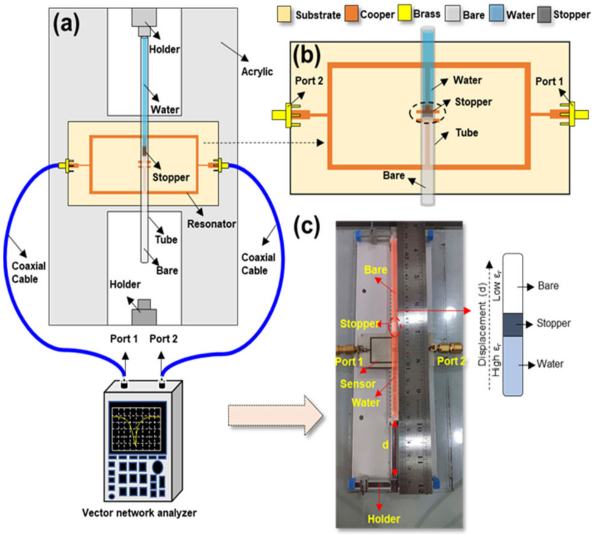

FIGURE 8. **(a) Scenario for liquid displacement detection, (b) detail structure of liquid displacement detection, (c) measurement setup for liquid displacement detection using proposed sensor.**

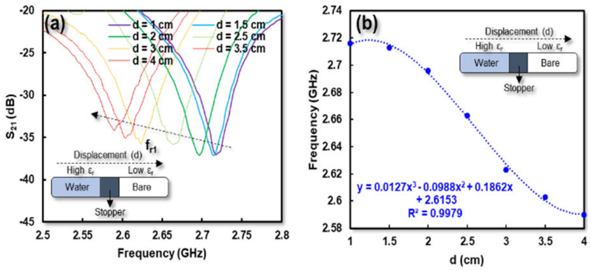

FIGURE 9. **(a) Measurement result of liquid displacement detection with d = 1 – 4 cm, (b) correlation between resonant frequency and liquid displacement with d = 1 – 4 cm.**

$$f_{r(c)} = \mathbf{0.01273}\,\boldsymbol{d}^{\mathbf{3}} - \mathbf{0.988}\,\boldsymbol{d}^{\mathbf{2}} - \mathbf{0.1862}\,\boldsymbol{d} - \mathbf{2.6153} \tag{2}$$

where $f_{r(b)}$ is the resonant frequency of the resonator for displacement detection and d represents the distance of the displacement in the water-filled polystyrene-mm pipe channel.

Moreover, the sensitivity (S) of the sensor is determined based on the following **Eq. (3)** [21]:

$$\mathbf{S} = \frac{\boldsymbol{\Delta F}\ (\boldsymbol{GHz})}{\boldsymbol{\Delta d}\ (\boldsymbol{cm})} \tag{3}$$

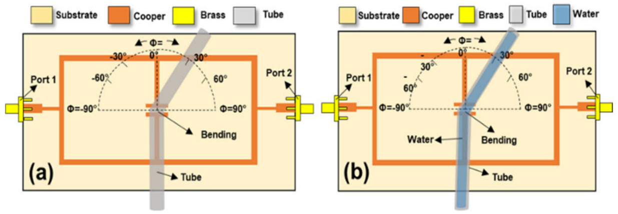

FIGURE 10. Scenario of angular detection from 0° - 90°; (a) without water, (b) with water.

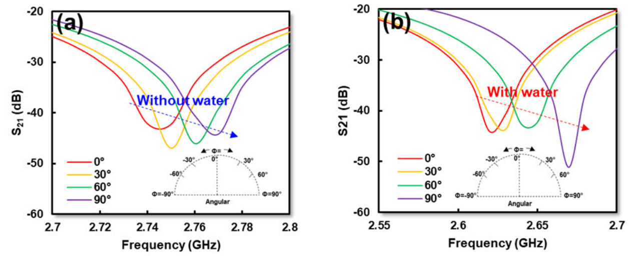

FIGURE 11. Simulation result of angular detection from 0° - 90°; (a) without water, (b) with water.

where ΔF represents the shift in the resonant frequency of the resonator and Δd represents the displacement of the sample in the polystyrene-mm pipe channel. Based on **Eq.** (3), the sensitivity of the sensor for displacement detection is 31.5 MHz/cm with a range d of 1 - 4 cm.

B. SCENARIO FOR LIQUID ANGULAR DETECTION

Furthermore, liquid angular detection is proposed by rotating the sample inside the polystyrene-mm pipe channel with an angle range of 0° - 90°. In this paper, the rotation of the sample in the polystyrene-mm pipe channel is divided into two conditions, including with water and without water as shown in **Fig.** 10 (a) and **Fig.**10 (b). The sample in the polystyrene-mm pipe channel is rotated clockwise at angles of 0°, 30°, 60° and 90°.

The simulation results in **Fig.**11 (a) and **Fig.**11 (b) show that the resonant frequency of the resonator shifts to a higher frequency in line with increasing the rotation angle of the sample for conditions without water and with water content. The resonant frequency shifts from 2.74 GHz to 2.77 GHz in conditions without water, while for conditions with water it shifts from 2.62 GHz to 2.67 GHz with an angle range of 0° - 90° as shown in **Fig.** 12 (a) and **Fig.** 12 (b).

Furthermore, validation of angular detection is carried out by measuring the process using a VNA connected to port 1 and port 2 of the resonator placed in the holder using a coaxial cable with an impedance of 50 Ω. The sample in the polystyrene-mm pipe channel is carefully placed in the sensing area which is located in the middle of the ELC resonator as shown in **Fig.**13 (a) and **Fig.**13 (b).

Moreover, to ensure that the sample position is constant and stable, a gripper is proposed in the measurement setup to lock the position of the sample and sensor. The measurement results of angular detection when the polystyrene-mm pipe channel is filled with water and without water are shown in **Fig.**14 (a) and **Fig.**14 (b).

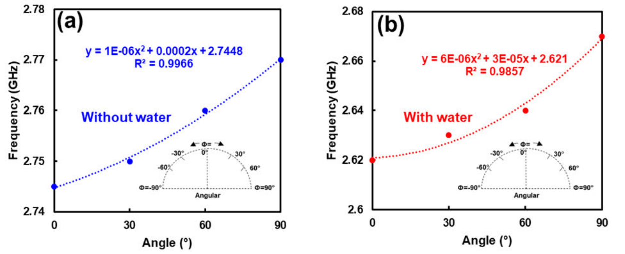

FIGURE 12. Simulation result of correlation between resonant frequency and angle from 0° - 90°; (a) without water, (b) with water.

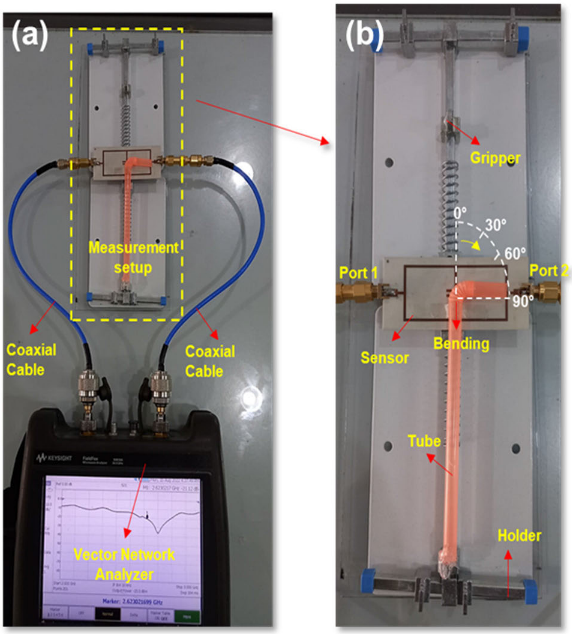

FIGURE 13. (a) Measurement setup with VNA, (b) Measurement scenario for angular detection from 0° - 90°.

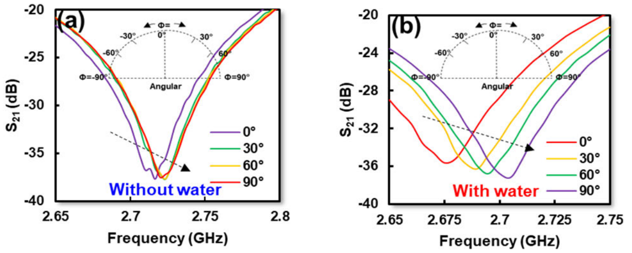

FIGURE 14. Measurement result of angular detection from 0° - 90°; (a) without water, (b) with water.

Based on the measurement results, the frequency of the resonator shifts from 2.716 GHz to 2.723 GHz when the polystyrene-mm pipe channel is without water, whereas when the polystyrene-mm pipe channel is filled with water, the frequency shifts from 2.675 GHz to 2.705 GHz with an angle range of 0° - 90° as shown in **Fig.**15 (a) and **Fig.**15 (b). These findings indicate that the proposed sensor interacts with the sample so that the resonant frequency of the resonator changes in line with an increase in the rotation angle of the sample in the polystyrene-mm pipe channel.

It should be noted, the resonance frequency shifts to a higher frequency due to the interaction of the sample and

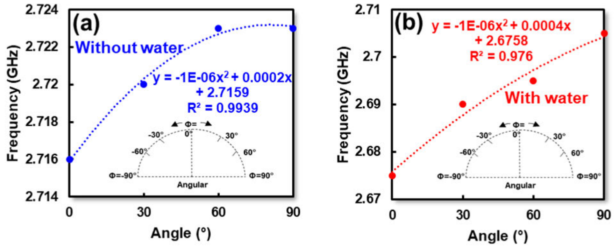

FIGURE 15. Measurement result of correlation between resonant frequency and angular from 0° - 90°; (a) without water, (b) with water.

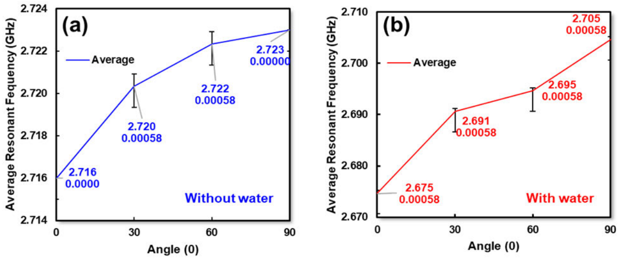

FIGURE 16. Average and deviation from repeatability measurement for angular detection; (a) without water, (b) with water.

sensor which changes while the sample inside polystyrene-mm pipe channel shifts away from the surface of the sensing area with water content to bare condition (without sample). In other words, the permittivity of the sample changes from higher to lower. This condition changes the concentration of the electric field of the resonator and greatly influences the resonant frequency of the resonator.

Furthermore, angular detection of polystyrene-mm pipe channel without and with water can be determined based on the following **Eq.** (4) and **Eq.** (5):

$$\boldsymbol{f_{r\,(ba)} = -0.000001\,x^2 - 0.0002\,x + 2.7159} \tag{4}$$

$$\boldsymbol{f_{r\,(bw)} = -0.000001\,x^2 - 0.0004\,x + 2.6578} \tag{5}$$

where $f_{r\,(ba)}$ and $f_{r\,(bw)}$ is the resonant frequency of the resonator for angular detection with and without water and x represents the angle of the angular in the water-filled polystyrene-mm pipe channel.

Moreover, the sensitivity (S) of the sensor is determined based on the following Eq. (6) [18]:

$$\boldsymbol{S = \frac{\Delta F\ (GHz)}{\Delta \theta\ (^\circ)}} \tag{6}$$

where ΔF represents the shift in the resonant frequency of the resonator and $\Delta\theta$ represents the rotation of the sample in the polystyrene-mm pipe channel.

Based on Eq. (6), the sensitivity of the sensor for angular detection of polystyrene-mm pipe channel without and with water content are 0.07 MHz/° and 0.33 MHz/° with a dynamic range of 0 - 90°. Moreover, average and deviation of repeatability measurements with 3 cycles are proposed to show the error bars of angular detection for sample filled in polystyrene-mm pipe channel with and without water using the proposed sensor as shown in **Fig.**16.

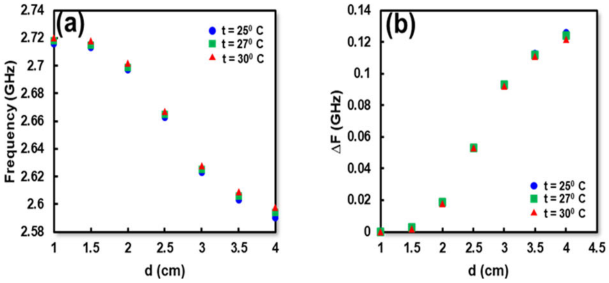

FIGURE 17. Displacement detection of liquid samples based on different temperatures; (a) response of the resonant frequency, (b) ΔF of proposed sensor.

Based on **Fig.**16 (a) and **Fig.** 16 (b), the deviation from the repeatability measurement results is in the range 0 - 0.00058 for angular detection with and without water. These findings indicate that the proposed sensor has a low error bar for angular detection in samples with and without water. To show the effect of changing the temperature of the liquid sample on displacement detection, validation with measurements at three different temperatures is proposed as shown in **Fig.** 17 (a) and **Fig.** 17 (b).

Referring to **Fig.**17 (a), changes in temperature in the sample have an impact on shifting the resonant frequency of the resonator towards high frequencies correlated with previous work [34] [39]. The maximum ΔF of the proposed sensor for three different temperatures are 0.126 GHz, 0.124 GHz and 0.122 GHz respectively as shown in **Fig.** 17 (b). The sensitivity of the sensor based on temperature changes is 31.5 MHz/cm, 31 MHz/cm and 30.5 MHz/cm respectively. These findings indicate that changing the temperature of the sample has an impact on the shift in the resonance frequency and sensitivity of the sensor but is not significant. Therefore, the temperature of the sample must be verified before the measurement process is carried out to obtain optimal performance.

IV. VALIDATION WITH PREVIOUS WORK

To validate the performance of the proposed sensor, a comprehensive evaluation with previous work is proposed as shown in **Table** 2. Based on previous work, the detection of linear and angular displacement of samples using microwave sensors are divided into three types of mechanisms based on frequency shift, phase variation and notch depth.

Previous work [1], [32] proposed a microwave sensor based on transmission line for displacement detection of solid materials with a maximum dynamic range of 3 - 40 mm and maximum sensitivity of 312.7 °/ mm and 528.7 ° / mm where the displacement detection was determined based on phase variations. However, the sensor only has one function for displacement detection and cannot be used for angular displacement of materials. Other works [7], [23] proposed a microwave sensor for displacement and rotation detection of solid materials based on notch depth with a maximum dynamic range of 10 mm and 90 °. Nevertheless, the proposed sensor only supports displacement detection in solid

TABLE 2. Comparison of proposed sensor based on displacement / rotation technique with existing works.

Ref	Method	Freq (GHz)	Sensing mechanism	Sample	Dynamic Range		Sensitivity Average		Polystyrene mm-pipe	Sensor Type		Dual Functional
					Displacement	Angular	Displacement	Angular		Displacement	Angular	
[1]	Step impedance transmission lines	2.00	Phase variation	Solid	0 – 40 mm	-	312.7°/ mm	-	-	Yes	-	-
[3]	H-shaped resonator	4.80 2.59	Freq shift	Solid	0 – 12 mm	-	147.8 MHz/mm	-	-	Yes	-	-
[7]	Dielectric resonator	3.70	Notch depth	Solid	1 – 10 mm	-	0.095 dB/ mm	-	-	Yes	-	-
[19]	Transversal signal interference	0.92	Freq shift	Solid	-	0 – 180°	-	3.15 MHz /°	-	-	Yes	-
[21]	CSRR	5.80	Freq shift	Solid	-	0 – 90°	-	2.37 MHz/°	-	-	Yes	-
[23]	Transmission line	1.21	Notch depth	Solid	-	0 – 90°	-	0.095 dB/°	-	-	Yes	-
[27]	TFS - coupled slot line	2.17	Freq shift	Solid	-	0 – 90°	-	2.27 MHz/°	-	-	Yes	-
[28]	U-shaped resonator	1.20	Freq shift	Solid	-	0 – 180°	-	1.94 MHz/°	-	-	Yes	-
[32]	Stepped impedance Transmission lines	2.00	Phase variation	Solid	0 – 3 mm	-	528.7°/ mm	-	-	Yes	-	-
This work	**ELC Resonator**	**2.72**	**Freq shift**	**Liquid**	**1 – 4 cm**	**0 – 90°**	**31.5 MHz/cm**	**0.33 MHz/°**	**Yes**	**Yes**	**Yes**	**Yes**

TABLE 3. Comparison of type, sensing parameters and prospective applications of displacement / rotation sensors.

Ref	Type of resonator	Sensing parameter	Prospective applications
[1]	Single port resonator	Phase	Industrial
[3]	Band stop filter	S_{21}	Industrial
[7]	Band pass filter	S_{21}	Industrial
[19]	Band stop filter	S_{21}	Industrial
[21]	Band stop filter	S_{21}	Space vehicle (satellites)
[23]	Band pass filter	Phase	Industrial
[27]	Band pass filter	S_{21}	Industrial
[28]	Band stop filter	S_{21}	Industrial
[32]	Band pass filter	S_{21}	Biomedical and energy
This work	Band stop filter	S_{21}	Industrial and Biomedical

materials so it cannot be used for liquid materials. Furthermore, detection of linear displacement of solid materials based on resonant frequency shifts has been described in [3] where the maximum dynamic range is 12 mm with a sensitivity of 147.8 MHz/mm. Rotation detection of solid materials based on frequency shift has also been described in [19], [21], [23], and [28] where the solid material is moved using a rotator and the sensor is placed on the stator. However, high friction between the material and the sensor has the potential to damage the surface of the resonator and will reduce the performance of the sensor.

Furthermore, a comprehensive comparison of types, sensing parameters and proposed applications of displacement and rotation sensors is shown in **Table 3**. Previous work [3], [19], [21], [23] proposed a band stop filter for displacement and rotation detection which is recommended for industrial applications including flow detection in liquids, space vehicle and rotation detection in AC motors. In addition, other work [7], [23], [27], [32] proposed a band stop filter for displacement/rotation detection which is recommended for industrial, biomedical and energy applications while previous work [1], proposed a single port resonator for motor rotation detection AC based on phase variations.

Therefore, this work makes a significant contribution by proposing a dual functional microwave sensor for translation and angular detection in liquid samples using polystyrene-mm pipe channels. The proposed sensor has the capability to detect displacement and angular detection separately based on the frequency shift of the resonator. Polystyrene-mm pipe channels are proposed to reduce the friction between the sensor and the sample and maintain the temperature of the sample in order to obtain high-precision measurements. The proposed sensor has excellent performance with a maximum sensitivity of 31.5 MHz/cm for liquid displacement with a range of d = 1 - 4 cm and 0.33 MHz/ ° for angular detection with an angle range of 0 – 90 °.

V. CONCLUSION

A microwave sensor with dual functional characteristics for liquid displacement and angular detection in polystyrene-mm pipe channel has been proposed and presented comprehensively in this paper. The proposed sensor is based on an ELC resonator operating at a resonant frequency of 2.72 GHz. The sample used is liquid material contained in a polystyrene-mm pipe channel. Displacement and angular detection are determined based on the shift in the resonant frequency of the resonator. Based on the measurement results, the proposed sensor has a sensitivity of 31.5 MHz/cm with a displacement range of 1 - 4 cm and 0.33 GHz /° with an angle range of 0 - 90°. This paper makes a significant contribution by proposed a dual functional microwave sensor for displacement and angular detection that can be recommended for the automotive, robotics and aerospace industries.

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