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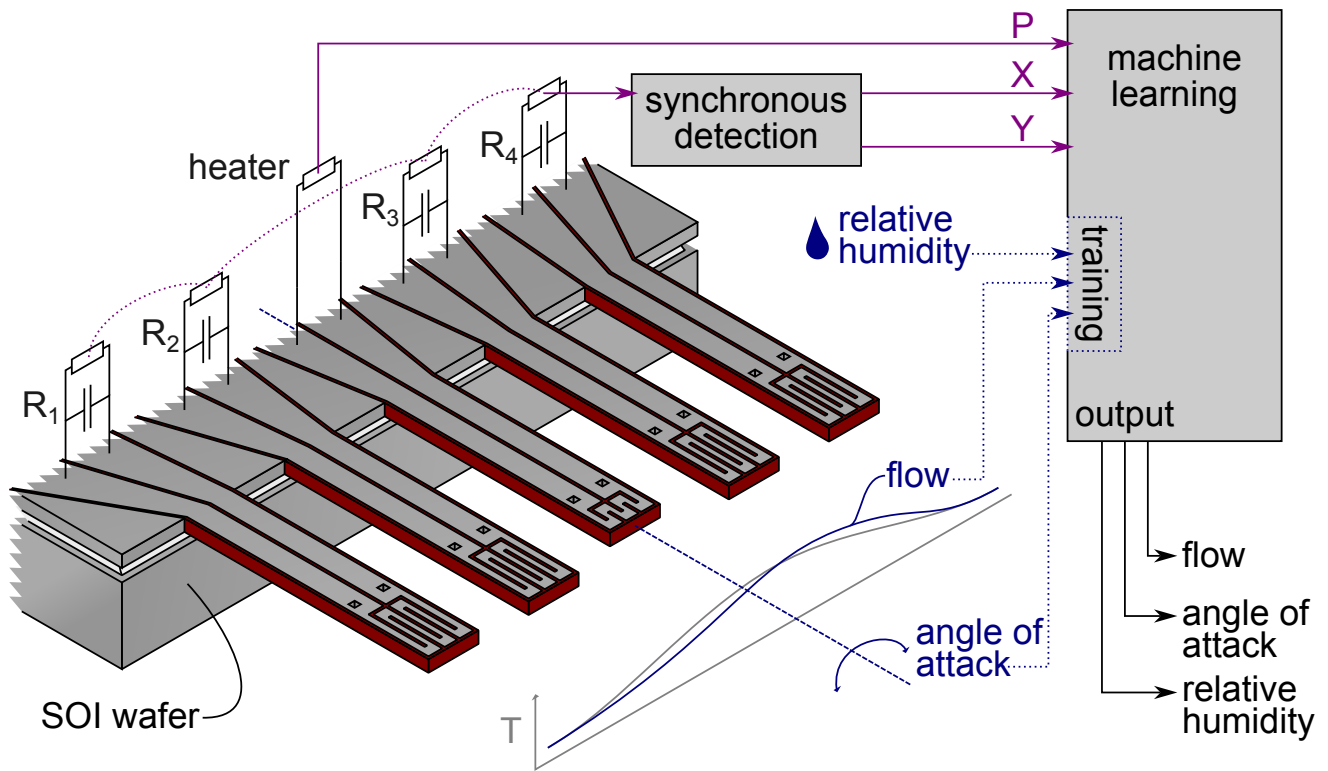
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REGULAR PAPERS

Sensor Phenomena

Combinations of Analytical and Machine Learning Methods in a Single Simulation Framework for Amphoteric Molecules Detection	<i>N. Kumar, P. Aleksandrov, Y. Gao, C. Macdonald, C. P. García, and V. Georgiev</i>	1501004
Study of AC Electrothermal Effect in Microfluidics	<i>Z. Bouchaar, Y. T. Set, L. Lagae, and C. D. M. Campos</i>	1501104
Unveiling Biosensing Innovations: Laser Scattering Sensor and Gold Nanoparticles-Decorated Ti ₃ C ₂ MXene Composite for Enhanced Biosensing Applications	<i>F. Pisani, A. Zaheer, Z. U. D. Babar, R. Velotta, C. Granata, F. Tessicini, B. D. Ventura, and V. Iannotti</i>	1501204
Contact Activation in Dielectric Blood Coagulometry: A Comparison of Screen-Printed and Sputtered Gold Electrodes of ClotChip Microfluidic Sensor	<i>H. Alizadeh, C. Abonga, C. A. Delianides, S. Pourang, M. A. Suster, and P. Mohseni</i>	1501304
Textile-Integrated Organic Electrochemical Transistor for Selective Ion Detection via Electrical Impedance Spectroscopy	<i>A. Altana, B. Shkodra, P. Ibba, M. A. C. Angeli, M. Ploner, M. Petrelli, E.-M. Korek, P. Lugli, and L. Petti</i>	1501404
Planar Ag/AgCl Reference Electrode for Electrochemical Agronomic Sensors	<i>S. Mamilla, S. Z. Yousuf, M. M. Avulapati, A.-A. Mallahi, and NVL N. Murty</i>	1501504
Geometry Optimization to Enhance the Range of Detection of Fringing Field-Based Capacitive Proximity Sensors	<i>Lekshmi V and J. Joseph</i>	1501604
The Effect of Poisson Ratio and Beam Width on the Fundamental Frequency of a Cantilever Beam	<i>E. Salman, L. Musnikov, D. Rosenstock, and D. Elata</i>	1501704
Design and Fabrication of Micro Resonator With Bilateral Concentric Boundaries	<i>H. Nazemi, R. Graham, B. Ye, D. Damiani, and A. Emadi</i>	1501804
Silver Dendrites Decorated AAO Membrane for SERS Sensing of Lactic Acid in Artificial Sweat	<i>C.-L. Sung, T.-T. Kao, and Y.-C. Lin</i>	1501904
Methodological Framework for Conductor Lifetime Estimation Using Optical Sag Sensors	<i>H. Singh, G. Fusiek, and P. Niewczas</i>	1502004

Sensor Materials

Smart-Textile-Based Electrochemical Capacitive Ionic Sensors for High-Performance Epidermal Electronics	<i>A. T. Mavelil, V. Sam, P. R. Markapudi, F. Paul, M. Beg, and L. Manjakkal</i>	2000704
Enhanced Performance of Calcium-Ion Selective Electrode Based on Chitosan/MXene/ZnO Modification	<i>Y. Liu, J. Zhai, H. Dong, B. Luo, and X. Wang</i>	2000804

Physical Sensors

Human Transferrin Detection Through a Mass-Sensitive Biosensor Utilizing ZnO Thin-Films via Atomic Layer Deposition	<i>O. Alev, A. Klç, M. Çoban, B. K. Tokyay, S. Büyükköse, S. Öztürk, and Z. Z. Öztürk</i>	2501504
---	---	---------

(Contents Continued on Next Page)

Flat Magnetic X–Y Alignment Sensor	<i>P. Ripka, M. Mirzaei, and J. Maier</i>	2501604
Inkjet-Printed Temperature Sensor From Eco-Friendly Edge-Oxidized Graphene Oxide Ink on Biodegradable Polyvinyl Alcohol Substrate	<i>J. Khan, M. Weis, and M. Mariatti</i>	2501704
Electromagnetic–Thermal Far-Infrared Detection Using Arrays of Schottky Barrier Diode Detectors in a Foundry CMOS Tuned at 20 Terahertz	<i>M. M. Farooq, B. Pouya, and K. K. O</i>	2501804
High-Q Wireless SAW Sensors Based on AlN/Sapphire Bilayer Structure, Operating at 2.45 GHz Range for High-Temperature Applications	<i>U. Youbi, S. Hage-Ali, Q. Zhang, Y. Yang, D. Ba, H. M’jahed, T. Aubert, and O. Elmazria</i>	2501904
<i>Electromagnetic Wave Sensors</i>		
Design and Optimization of Angle-Dependent Grating Couplers for Wideband Near-Mid Infrared Transmission	<i>A. Mishra, K. K. Rana, and T. Srinivas</i>	3501204
Collaboratively Far-Field and Near-Field Regions for Dual-Modalities Microwave Permittivity Sensor Using T-Shaped Resonator Embedded With IDC	<i>S. Alam, Z. Zakaria, I. Surjati, N. A. Shairi, M. Alaydrus, T. Firmansyah, Y. K. Ningsih, and L. Sari</i>	3501304
Two-Stage Zoom FFT-Enhanced Deep Learning-Aided Weighted Scheme for Wireless Vital Sign Estimation Using mmWave FMCW Radar	<i>H.-Y. Chang, Y.-Y. Chen, and W.-H. Chung</i>	3501404
Clear Image Acquisition by 3D High-Speed Vibration Tracking of Object With Various Shapes Under High Magnification	<i>S. Yonezu and Y. Yamakawa</i>	3501504
Towards Localization of Miniaturized Medical Robots With Microwaves	<i>Y.-H. Lin, H. Daguerre, A. Lavrenko, and S. Misra</i>	3501604
<i>Chemical and Biological Sensors</i>		
Ultrasensitive Detection of Lead Ions Through Portable Sensor Technology for Enhanced Environmental Monitoring	<i>A. Gupta, D. Rotake, and A. Darji</i>	4501504
Development of Molecular-Imprinted Electrochemical Sensor for Linolenic Acid	<i>J. Cui, H. Zhang, K. Liu, Z. Zhou, and A. Li</i>	4501604
Comparison of Aptamer and Antibody Bioreceptors in the OEGFET Biosensor Platform for Detecting α -Synuclein, a Parkinson’s Biomarker	<i>R. S. Massey, S. Johri, D. Chan, M. R. Holahan, and R. Prakash</i>	4501704
Integrated Subpixel-Patterned LSPR Gas Sensor via Inkjet Printing of Au/Ag Nanoparticles and Pigments for Multigas Detection	<i>T. Jiang, X. Ye, H. Guo, C. Wang, L. Ge, F. Sassa, and K. Hayashi</i>	4501804
<i>Sensor Systems</i>		
RFID-Based Multisensory System for Environmental Monitoring and Consumable Management of Intelligent Tracking	<i>Y. An, W. Kong, Y. Bo, N. N. Xu, and J. Yang</i>	5502104
A Capacitive Sensor Readout IC With Antenna-Integrated Sensor for Proximity Detection in Handheld Mobile Devices	<i>T.-L. Hsu, A. Hagelauer, and V. Solomko</i>	5502204
Portable Multiplexed System-Based AD5933 Impedance Analyzer: Toward Multiselective Gas Recognition	<i>L. Routier, A. Westrelin, A. Cerveaux, P. Foulon, G. Louis, T. Horlac’h, K. Lmimouni, S. Pecqueur, and B. Hafsi</i>	5502304
Texture Perception Using Tactile Sensing Glove Based on PVDF Sensors and Machine Learning	<i>Y. Abbass, C. Gianoglio, H. A. H. Ali, M. Saleh, and M. Valle</i>	5502404
Differential Profile Diagram for Breast Tumor Classification Using Vibro-Acoustic Tactile System	<i>N. Rahman and C.-H. Won</i>	5502504
Electrothermal Tunable MEMS Oscillators for MEMS-Based Reservoir Computing	<i>Y.-C. Lee, L.-K. Wang, Y.-C. Chuang, H.-C. Hong, and Y. Chiu</i>	5502604
<i>Sensor Applications</i>		
An Ensemble Learning-Assisted Obstructive Sleep Apnea Detection Model Using EEG Physiological Signals and Improved Extra Tree Classifier	<i>A. Khan, S. Kr. Biswas, and C. Chunka</i>	6006604
Temperature Sensing Insoles for Diabetic Foot Ulcer Diagnostics	<i>P. G. Schmalen and T. Meyer</i>	6006704
A Wireless Wearable Ecosystem for Social Network Analysis in Free-Living Animals	<i>M. Gaidica, M. Zhang, and B. Dantzer</i>	6006804
Large Area Flexible Piezoresistive Sensor Array for Smart Mattress Application	<i>A. M. Hussain</i>	6006904
Acoustic Dipole Metalens for Far-Field Emission Enhancement	<i>D. W. Swett</i>	6007004
Soft and Flexible Wireless Epidermal Plaster Made by Laser-Induced Graphene	<i>A. Mostaccio, F. Naccarata, F. M. C. Nanni, J. Filippi, E. Martinelli, and G. Marrocco</i>	6007104

VibroTact: Soft Piezo Vibration Fingertip Sensor for Recognition of Texture Roughness via Robotic Sliding Exploratory Procedures	<i>Q. Guo, G. A. Al, and U. Martinez-Hernandez</i>	6007204
Use of a Multiscale Vision Transformer to Predict Nursing Activities Score From Low-Resolution Thermal Videos in an Intensive Care Unit	<i>I. YL Lee, T. Nguyen-Duc, R. Ueno, J. Smith, and P. Y Chan</i>	6007304
Assessment of Samsung Galaxy Watch4 PPG-Based Heart Rate During Light-to-Vigorous Physical Activities	<i>C. S. Lima, F. C. Bertocco, J. I. V. de Oliveira, T. M. F. de Souza, E. P. da Silva, and F. J. Von Zuben</i>	6007404
Fabrication and Analysis of Copper Textrode Characteristics for Monitoring Heart Biopotentials During Physical Activity	<i>M. Anandan, P. Veluswamy, A. Majumdar, and R. Palanisamy</i>	6007504
Novel Planar Passive Wireless Thin Film LC Temperature Sensor	<i>K. Rivera</i>	6007604
In the Realm of Aerial Deception: UAV Classification via ISAR Images and Radar Digital Twins for Enhanced Security	<i>A. N. Sayed, O. M. Ramahi, and G. Shaker</i>	6007704
Wavelet-Based Convolutional Neural Network for Denoising Partial Discharge Signals Extracted via Acoustic Emission Sensors	<i>C. Kumar, B. Ganguly, D. Dey, and S. Chatterjee</i>	6007804
A Zero-Power Harmonic Tag for Real-Time Wireless Food Quality Monitoring	<i>Y. Ren, N. Wu, K.-C. Chang, Y.-S. Su, and P.-Y. Chen</i>	6007904
L3D-OTVE: LiDAR-Based 3-D Object Tracking and Velocity Estimation Using LiDAR Odometry	<i>A. Thakur and P. Rajalakshmi</i>	6008004
Machine Learning-Based Methods for Force Mapping With an Optical Fiber Sensing System	<i>W. O. C. Flores, V. Carvalho, V. H. Martins, J. L. Fabris, M. Muller, H. S. Lopes, and A. E. Lazaretti</i>	6008104
Multichannel Eigenvalue Decomposition of Hankel Matrix-Based Classification of Eye Movements From Electrooculogram	<i>V. K. Singh and R. B. Pachori</i>	6008204
A Machine Learning Enhanced MEMS Thermal Anemometer for Detection of Flow, Angle of Attack, and Relative Humidity	<i>T.L. Hackett, J. Choi, R. G. P. Sanders, T. E. vd. Berg, D. Alveringh, and J. Schmitz</i>	6008304
Health Indicator Analysis in Terms of Condition Monitoring on Brownfield CNC Milling Machines Using Triaxial Accelerometer	<i>P. Esmaili and L. Cristaldi</i>	6008404
Identification and Quantification of Multiple Drugs by Machine Learning on Electrochemical Sensors for Therapeutic Drug Monitoring	<i>L. Du, F. Rodino, Y. Thoma, and S. Carrara</i>	6008504
<i>Sensor Signal Processing</i>		
Geiger Mode Avalanche Photodiode Array With On-Chip Data Cache Suitable for Multiple Photon Echoes Detection	<i>J. Wu, D. Lv, C. Wan, J. Li, and L. Zheng</i>	7003504
<i>Sensor Networks</i>		
Investigating the Impact of Optimal Data Transfer Intervals on Failure-Prone Wireless Sensor Networks	<i>M. A. Amrizal, S. Y. Pradata, M. R. Sudha, L. Wang, and R. Pulungan</i>	7500604

About the Cover: A Machine Learning Enhanced MEMS Thermal Anemometer for Detection of Flow, Angle of Attack, and Relative Humidity (see Article Number 6008304).

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These category titles will appear in the journal TOC and gather all papers within the issue under each category.

Front Material

- 00 Cover
- 01 Tables of Contents
- 02 Society/Publication Information
- 03 Editorial
- 04 Awards
- 05 Memoriam
- 10 (PERS): Perspective Article
- 15 (PHEN): Sensor Phenomena
 - MODL: Modeling and Simulations
- 20 (MATR): Sensor Materials
- 25 (PHYS): Physical Sensors (including the following areas):
 - MECH: Mechanical Sensors
 - THER: Thermal Sensors
 - MAGN: Magnetic Sensors
 - MASS: Mass Sensors
- 35 (OPTO): Electromagnetic Wave Sensors (including the following areas):
 - OPT: Optical Sensors
 - MICR: Microwave/Millimeter Wave Sensors
 - ION: Radiation Sensors
- 45 (CHEM): Chemical and Biological Sensors
- 50 (INTG): Sensor Integration (including the following area):
 - ACTU: Sensor-Actuators
- 55 (SYST): Sensor Systems
- 60 (APPL): Sensor Applications
- 65 (PACK): Sensor Packaging
- 70 (SIGP): Sensor Signals Processing
- 75 (NET): Sensor Networks

Back Material

- 96 Comments
- 97 Corrections/Errata
- 98 Announcements
- 99 Other

Collaboratively Far-Field and Near-Field Regions for Dual-Modalities Microwave Permittivity Sensor Using T-Shaped Resonator Embedded With IDC

Syah Alam^{1*}, Zahriladha Zakaria^{2**}, Indra Surjati^{1*}, Noor Azwan Shairi^{2*},
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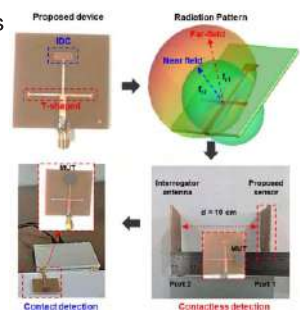
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Abstract—This letter introduces collaboratively far-field and near-field regions for dual-modalities permittivity sensor to characterized solid materials. The proposed sensor comprises a T-shaped resonator featuring a single port embedded with interdigital capacitor (IDC). The first resonator, operating at $f_{r1} = 2.43$ GHz as the long-distance detection, utilizes the far-field region, while the second resonator, working at $f_{r2} = 1.64$ GHz, functions as the contact detection, utilizes the near-field region. These resonators possess distinct sensing hotspots, enabling independent utilization. Contact detection is achieved by utilizing the near-field region by placing the material under test (MUT) directly above the surface of the second resonator, while the first resonator for long-distance detection utilized the far-field region by using the interrogator antenna at a distance of $d = 10$ cm. The experimental results demonstrate that the proposed sensors exhibit a maximum sensitivity of 5.13% and 3.40% for near-field and far-field detections, respectively. Moreover, the average accuracy for both contact and long-distance detections is 95.99% and 95.16%, respectively, when compared to the permittivity values obtained from the datasheet within the range of 1–6.15. This research holds significant practical value for the contact and long-distance characterizations of solid materials, particularly in applications, such as biomedical, quality control, and pharmaceutical industries.



Index Terms—Microwave/millimeter wave sensors, dual modalities, far field, microwave sensor, near field, solid materials.

I. INTRODUCTION

Microwave sensors (MS) have gained widespread development for assessing both solids and liquids due to their benefits, including high precision, a high Q-Factor, affordability, and compact size [1]. One of the properties they can detect is permittivity, which refers to a material's capacity to retain an electric field. Moreover, permittivity of the material under test (MUT) can be ascertained through perturbation theory, assuming that the MUT acts as a capacitive load [2]. Previous studies have put forth various MS employing resonators, such as split ring resonator (SRR) [3], complementary SRR [4], substrate-integrated waveguide [5], and interdigital capacitor (IDC) [6] for assessing solid substances. In contrast, previous work proposed by Alam et al. [7] introduces a dual T-shaped resonator featuring a single port for characterizing solid materials with contact and noncontact. However, this work has disadvantages, such as a very limited distance of 0.5–1.5 mm for noncontact detection, poor sensitivity, and the fact that the locations of the E-field and H-field are ambiguous. Another work, presented in [8], suggests a multifunctional dual-band MS

with an antenna for communication purposes. However, the MUT's characterization is only performed directly by placing it on the sensing hotspot. In addition, the authors in [9] and [10] employed an antenna as a permittivity sensor for contactless detection at a distance of 20 and 30 mm using artificial magnetic conductor. However, the proposed sensor features only one sensing hotspot and therefore cannot facilitate contact and long-distance characterizations independently. Therefore, several requirements are needed to obtain high-performance MS with long-distance detection, high sensitivity, clear location between E-field and H-field, and dual hotspot location for contact and long distance.

To fulfill this requirement, this letter introduces a collaboration between near-field and far-field regions for microwave permittivity sensors operating at two resonant frequencies. In detail, the main contribution of this research, such as the proposed long-distance detection MS with two independent sensing hotspots, enables contact and long-distance characterizations of solid materials. To obtain a clear location between E-field and H-field with high sensitivity performance, a T-shaped resonator embedded with IDC was proposed. The first resonator operates at $f_{r1} = 2.43$ GHz for long-distance detection and the second resonator operates at $f_{r2} = 1.64$ GHz for contact detection. Furthermore, near-field and far-field regions for permittivity detection are determined based on S_{11} and the radiation pattern of the two

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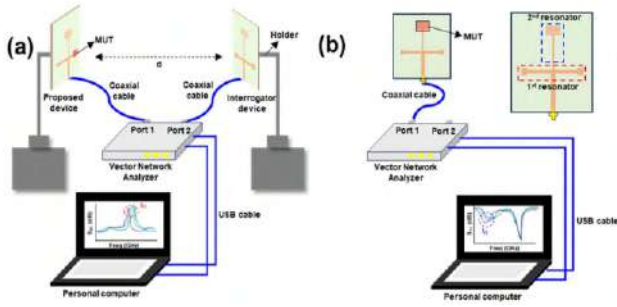


Fig. 1. Scenario of permittivity detection using proposed sensor. (a) Scenario (1) for long-distance detection using an interrogator antenna. (b) Scenario (2) for contact detection.

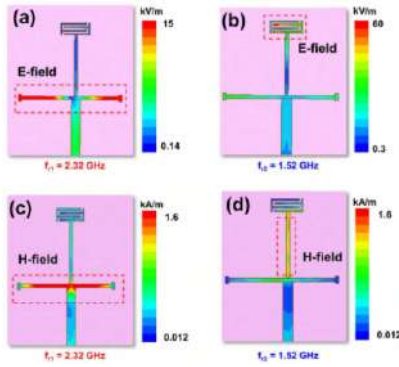


Fig. 2. (a) E-field at f_{r1} . (b) E-field at f_{r2} . (c) H-field at f_{r1} . (d) H-field at f_{r2} .

resonators, while for distance of (d), refer to Fresnel region with $d \geq \frac{2D^2}{\lambda}$ [11].

II. SENSOR DESIGN

A. Scenario of Near-Field and Far Field Regions for Characterization of Solid Materials

In this letter, two scenarios are proposed for far-field and near-field regions for the characterization of solid materials using the proposed sensor, as shown in Fig. 1(a) and (b), with the following explanation.

- 1) Furthermore, scenario (1) proposes long-distance detection using interrogator antennas operating at the same resonance frequency as the first resonator at $f_{r1} = 2.32$ GHz with $S_{11} \leq -10$ dB and separated by distance (d) of 10 cm. Long-distance permittivity detection is carried out by observing changes in the resonant frequency based on S_{21} , as shown in Fig. 1(a).
- 2) For scenario (2), near-field region for contact detection is proposed by placing the MUT on the IDC of the second resonator operating at $f_{r2} = 1.52$ GHz with $S_{11} \geq -10$ dB by observing changes in the resonant frequency based on S_{11} , as shown in Fig. 1(b).

The location of the sensing hotspot is determined based on the concentration of the E-field and H-field of the proposed resonator. The surface of the resonator with high E-field can be used to detect the permittivity of MUT. The E-field and H-field concentrations of the resonator are shown in Fig. 2(a)–(d).

Fig. 2(a) and (c) shows that the high E-field and H-field concentrations at $f_{r1} = 2.32$ GHz are at the same location on the arms of the first resonator. Other findings, as shown in Fig. 2(b) and (d), show that the highest E-field is in the gap of the IDC while the H-field is

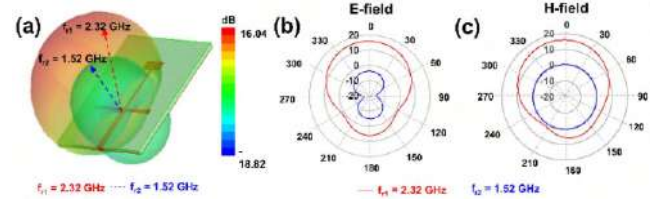


Fig. 3. (a) Radiation pattern of the proposed resonator at $f_{r1} = 2.32$ GHz and $f_{r2} = 1.52$ GHz. (b) E-field at $f_{r1} = 2.32$ GHz and $f_{r2} = 1.52$ GHz. (c) H-field at $f_{r1} = 2.32$ GHz and $f_{r2} = 1.52$ GHz.

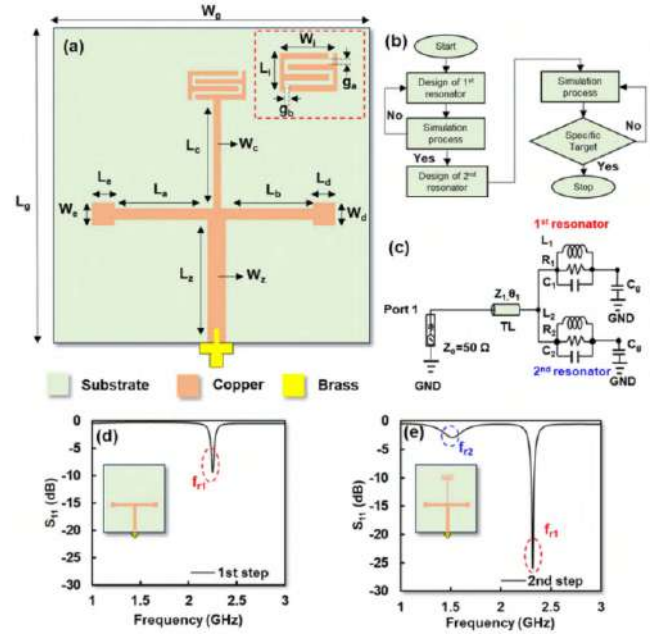


Fig. 4. (a) Structure of T-shaped resonator. (b) Flowchart of design process. (c) Equivalent circuit. (d) First step model. (e) Second step model.

in the arm of the second resonator. Furthermore, simulations of the radiation patterns at $f_{r1} = 2.32$ GHz and $f_{r2} = 1.52$ GHz are shown in Fig. 3(a)–(c).

Fig. 3(a) shows that the radiation pattern at $f_{r1} = 2.32$ GHz is higher than $f_{r2} = 1.52$ GHz. This finding is also in line with the simulations of E-field and H-field radiations shown in Fig. 3(b) and (c), respectively. This shows that resonators with high radiation can be used for long-distance detection by utilizing the far-field region, while low radiation can be used for contact detection by utilizing the near-field region.

B. Structure of Proposed Sensor

The dual modalities sensor is constructed utilizing of FR-4 substrate with specific properties: a dielectric constant (ϵ_r) of 4.3, a loss tangent ($\tan \delta$) of 0.0265, and a thickness (h) of 1.6 mm.

The configuration of T-shaped resonator and IDC can be observed in Fig. 4(a). Detailed dimensions of the proposed T-shaped resonator can be described as follows: $W_z = 3$ mm, $L_z = 17$ mm, $L_a = 16$ mm, $L_b = 12.5$ mm, $L_c = 18$ mm, $L_d = L_e = 1$ mm, $W_d = W_e = 2$ mm, and $W_g = L_g = 50$ mm, while for IDC represented by $W_i = 9.5$ mm, $L_i = 3.5$ mm, and $g_a = g_b = 1$ mm. Moreover, the flowchart of the design process dual T-shaped resonator is presented in Fig. 4(b) while for equivalent circuit shown in Fig. 4(c). In the initial phase, the resonator functions at $f_{r1} = 2.32$ GHz, as shown in Fig. 4(d), while in the subsequent phase,

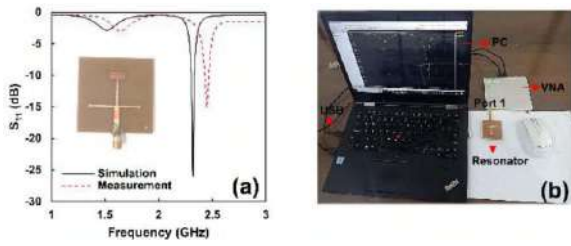


Fig. 5. (a) Comparison simulation and measurement result of proposed resonator. (b) Measurement setup of proposed resonator.

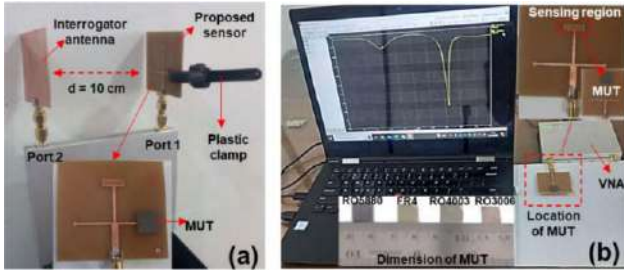


Fig. 6. Measurement setup. (a) Long-distance detection using scenario (1). (b) Contact detection using scenario (2).

it operates at a dual-band resonant frequency, with $f_{r1} = 2.32$ GHz and $f_{r2} = 1.52$ GHz, as shown in Fig. 4(e), respectively.

III. MEASUREMENT AND VALIDATION

A. Measurement of Proposed Sensor

Furthermore, Fig. 5(a) demonstrates that the measurement setup while the outcomes are consistent and exhibit dual-band characteristics in accordance with the simulated results, as shown in Fig. 5(b). Nonetheless, there is a slight deviation in the resonant frequencies of the resonator. Specifically, f_{r1} shifts from 2.32 to 2.43 GHz, with S_{11} of -15.05 dB, and f_{r2} shifts from 1.52 to 1.64 GHz, with S_{11} of -3.01 dB. This discrepancy can be attributed to minor variations in the fabrication process and inherent fluctuations in the permittivity of the FR-4 substrate, ranging from 3.8 to 4.8 [12].

B. Experimental Validation

The experimental validation was conducted utilizing a vector network analyzer spanning a frequency range of 1–3 GHz, with a frequency sweep increment of 0.01 GHz. The ambient temperature during the measurements was maintained at 25 °C. In addition, four distinct materials with known permittivity were employed as MUT: RO5880 possessing a permittivity of 2.20, RO4003 of 3.65, FR-4 of 4.30, and RO3006 of 6.15 with the dimension of MUT is $10 \times 10 \times 1.6$ mm³. Moreover, to ensure that the location of the MUT is constant, we carefully place the MUT at the location of the sensing hotspot using plastic clamp, which is for contact detection on the surface of the IDC and for long-distance detection on the surface of the T-shaped resonator, as shown in Fig. 6(a) and (b). Furthermore, Fig. 7(a) shows that f_{r1} shifts to low frequency in line with the increased permittivity of the MUT placed at the sensing hotspot of the first resonator for long-distance detection with $d = 10$ cm, while f_{r2} is fixed. The resonant frequency of the first resonator shifted from 2.43 to 2.35 GHz with a permittivity range of 1–6.15, as shown in Fig. 7(c).

In the other hand, Fig. 7(b) shows the performance of the proposed sensor for contact detection. It is evident that f_{r2} experiences a

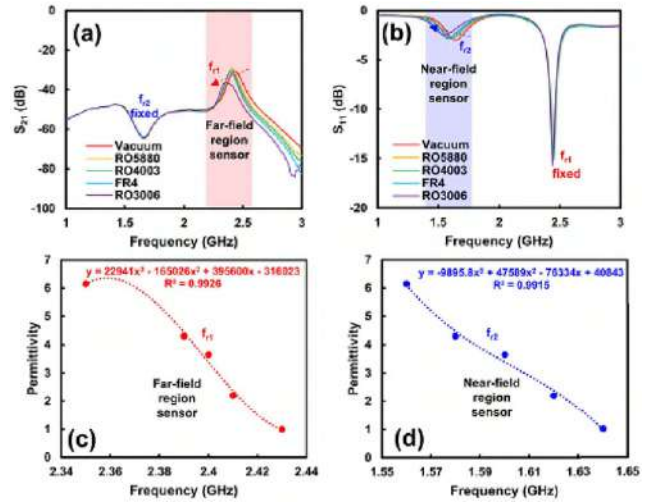


Fig. 7. Permittivity detection using proposed sensor. (a) Long-distance detection with $d = 10$ cm. (b) Contact detection. (c) Polynomial equation for long-distance detection. (d) Polynomial equation for contact detection.

TABLE 1. Performance of Proposed Sensor

MUT	ϵ_r ref	Δf (GHz / $\Delta\epsilon_r$)		Sensitivity (%)		Accuracy (%)	
		f_{r1}	f_{r2}	f_{r1}	f_{r2}	f_{r1}	f_{r2}
Vacuum	1.00	0	0	-	-	97.91	95.64
RO5880	2.20	0.02	0.02	0.83	1.23	92.38	92.08
RO4003	3.65	0.03	0.04	1.25	2.50	92.65	92.84
FR4	4.30	0.04	0.06	1.67	3.80	97.08	95.95
RO3006	6.15	0.08	0.08	3.40	5.13	99.93	99.29

downward shift in resonant frequency, corresponding to the increased permittivity of the MUT positioned on the sensing hotspot of the second resonator, whereas f_{r1} remains constant. Moreover, Fig. 7(d) shows that f_{r1} shifted to the lower frequency from 1.64 to 1.56 GHz in line with the increased permittivity of the MUT placed on the first resonator, while f_{r2} was fixed for permittivity range of 1–6.15.

C. Sensitivity and Accuracy of Proposed Sensor

The sensitivity of the microwave sensor is determined from the shift in the resonant frequency when the MUT is placed on the sensing hotspot. The frequency shift is represented as Δf , which shows the difference between the loaded and unloaded frequencies of the resonator. The frequency shift (Δf), sensitivity (S), and frequency detection resolution (FDR) of the microwave sensor can be determined using the following [13], [14]:

$$\Delta f = (f_{\text{unloaded}} - f_{\text{loaded}}) \text{ GHz} \quad (1)$$

$$S = \left(\frac{f_{\text{unloaded}} - f_{\text{loaded}}}{f_{\text{unloaded}}} \right) \% \quad (2)$$

$$\text{FDR} = \frac{\Delta F}{\Delta \epsilon_r} \quad (3)$$

where Δf represents frequency shift in Gigahertz, S represents the sensitivity of the sensor in percentage, f_{unloaded} represents the resonance frequency of the resonator before being loaded by the MUT, and f_{loaded} represents the frequency of the resonator when it is loaded with an MUT. In this letter, the f_{unloaded} used is when the resonator with

TABLE 2. Comparison With Previous Work

Ref	f_r (GHz)	Range of ϵ_r	Dimension (mm)		Num. of sensing hotspot	d (mm)	FDR (GHz)	S (%) / Q-factor	Separated E and H fields	Contact /long-distance detection
			Sensor	Sample						
[7]	1.81/2.34	1–6.15	50 × 50	10 × 10 × 1.6	2	1.5	0.023/0.003	2.30/117	No	Yes/No
[8]	1.50/2.00/2.45	1–6.15	50 × 50	10 × 10 × 1.6	2	0.0	0.013/0.027	2.71/120	No	Yes/No
[9]	6.90	1–15	40 × 40	10 × 10 × 4	1	20	0.038	3.80/69	No	No/Yes
[10]	4.04	2–4	30 × 30	25 × 25 × 2.1	1	30	NA	1.89/268	No	No/Yes
T.W.	1.64/2.43	1–6.15	50 × 50	10 × 10 × 1.6	2	100	0.016/0.016	5.13/121	Yes	Yes/Yes

permittivity of vacuum $\epsilon_r = 1$. Based on the calculations using (1) and (2) shows that the maximum Δf of the first and second resonators has the same value of 0.08 GHz / $\Delta \epsilon_r$ while the average sensitivities are 1.43% and 2.53%, respectively. The permittivity of the MUT is extracted using a polynomial equation obtained from the shift in the resonant frequency of the resonator, as shown in Fig. 7(b) and (d). Therefore, the permittivity of the MUT for both detections can be determined using the following:

$$\epsilon_{r1} = 22941f_{r1}^3 - 165026f_{r1}^2 + 395600f_{r1} - 316023 \quad (4)$$

$$\epsilon_{r2} = -9895.8f_{r2}^3 + 47589f_{r2}^2 - 76334f_{r2} + 40843 \quad (5)$$

where f_{r1} is the resonant frequency of the first resonator, and ϵ_{r1} is the permittivity of the MUT used for long-distance detection, while f_{r2} is the resonant frequency of the second resonator and ϵ_{r2} is the permittivity of the MUT used for contact detection. The overall performance of the proposed sensors both for long distance and contact detections are given in Table 1.

Moreover, FDR of the proposed sensor based on (3) for f_{r1} and f_{r2} are 0.016 GHz. Table 2 tabulates that the MS has novel dual modalities for contact and long-distance detection by utilizing the near-field and far-field regions with a high sensitivity of 5.13%, long-distance detection with $d = 100$ mm, and maximum Q-factor of 121 for solid materials with a permittivity range of 1–6.15 and two different sensing hotspots, compared with previous work, which only supports contact or long-distance detection and limited distance for long-distance detection.

IV. CONCLUSION

In this letter, dual modalities microwave sensor for long-distance and contact detections by utilizing the far-field and near-field regions has been successfully designed and realized. The MS consists of T-shaped resonators embedded with IDC operating at $f_{r1} = 2.43$ GHz and $f_{r2} = 1.64$ GHz with different sensing hotspots and have independent characteristics. From the measurement results, a maximum sensitivity of 3.40% and 5.13% was obtained for long-distance detection using the interrogator antenna with a distance (d) = 10 cm and contact detection. Furthermore, the average accuracy of the first and second resonators is 95.99% and 95.16%, respectively. The proposed sensor can be a promising solution and can be recommended for contact and long-distance characterization of solid materials for biomedical, pharmaceutical, and quality control industries.

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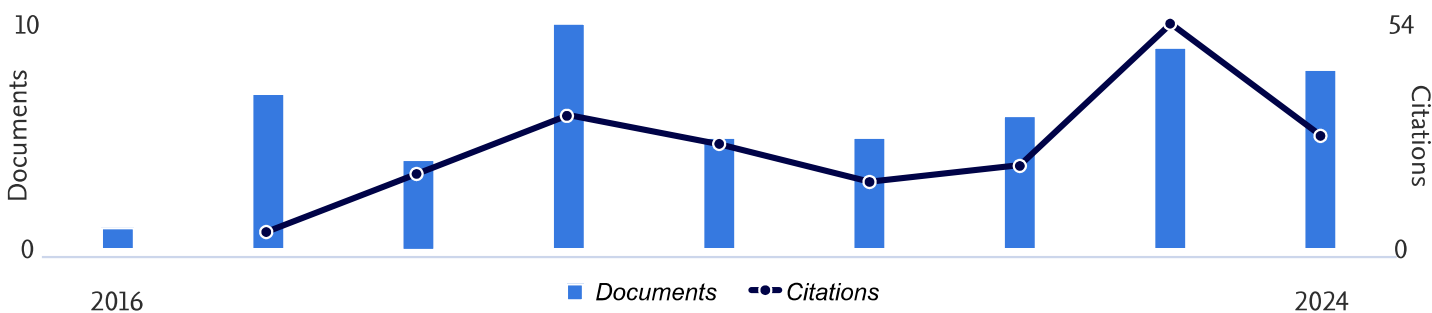
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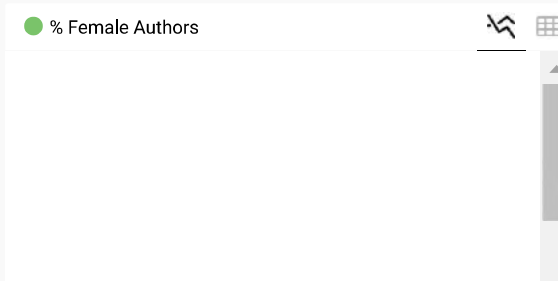
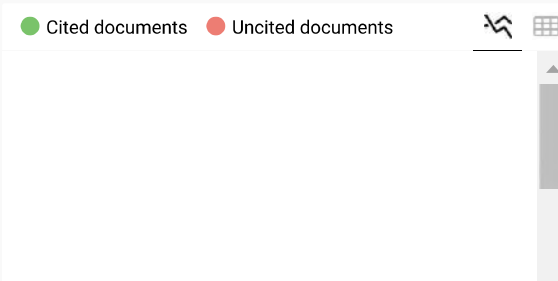
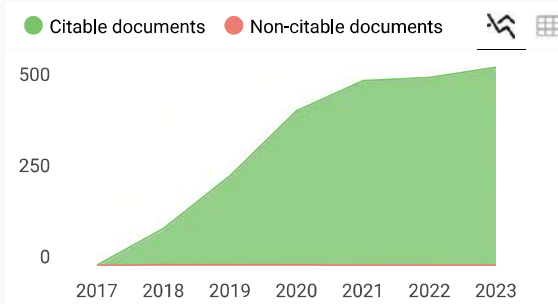
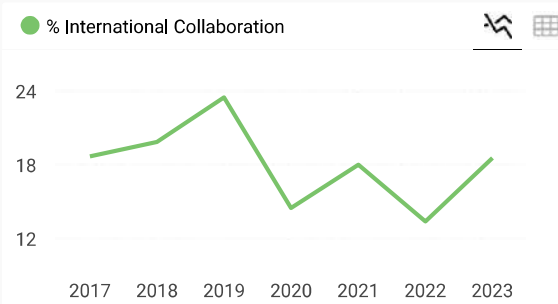
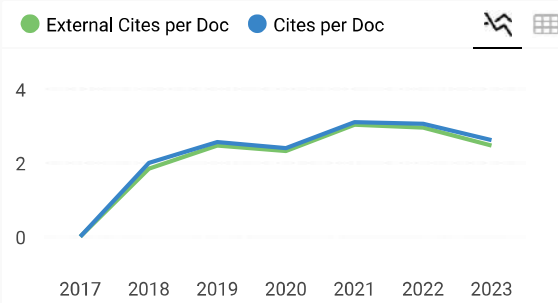
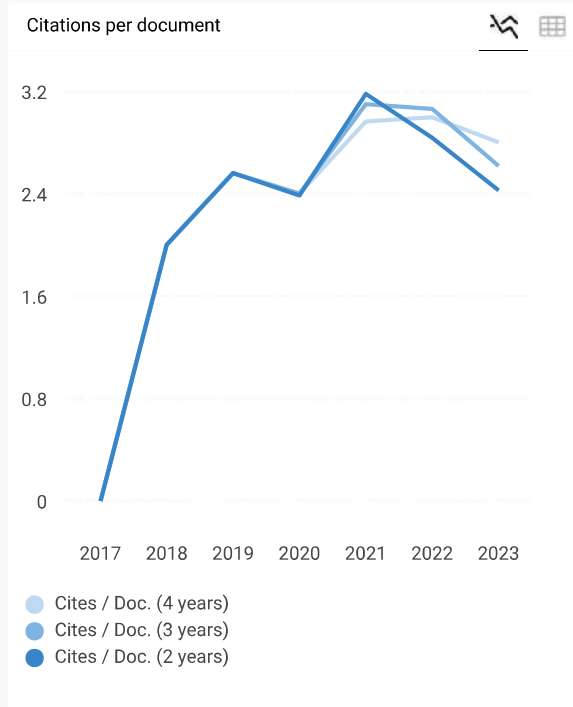
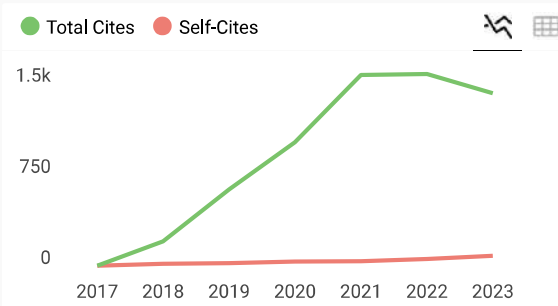
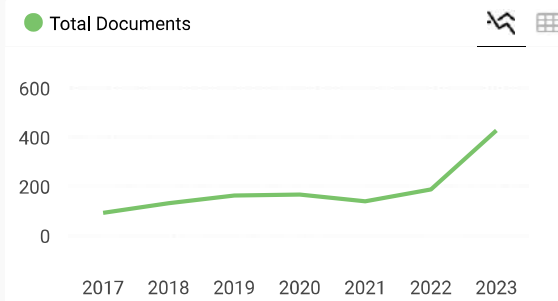
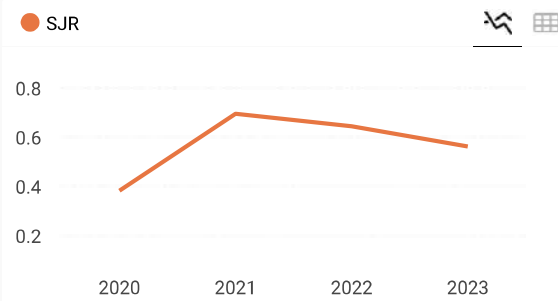
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