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Close Quarters Permittivity Detection Based on Tagging Antenna Sensor for Solid Material Characterization

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ABSTRACT: This research proposes a tagging antenna sensor for permittivity detection of solid materials based on a close quarter approach. The sensor is proposed to operate at a frequency of 2.53 GHz using a single port resonator with a reflection coefficient $(S_{11}) \leq -10$ dB. The sample is placed directly in the sensing area of the antenna sensor based on the concentration of the electric field. Permittivity detection is proposed based on the resonant frequency shift of the transmission coefficient (S_{21}) using interrogator antennas separated by a distance of $(d) = 100$ mm determined using the Fresnel region. Based on the measurement results, the antenna sensor has a high accuracy of 96% while the sensitivity and ΔF are 0.39% and 0.012 GHz, respectively. Moreover, the sensitivity ofthe proposed sensor is still low due the low concentration of the electric field. Therefore, increasing the sensitivity of the antenna sensor can be recommended as further work such as combining the structure of single port resonator with another structure such as interdigital capacitor and artificial magnetic conductor (AMC). Finally, this research makes a significant contribution to the permittivity detection of solid materials with a close quarter approach to support real time and flexible measurements and can be recommended for several applications for the biomedical, pharmaceutical, and material quality control industries.

1. INTRODUCTION

Material characterization is important for observing the performance and interaction of materials under certain conditions [1]. One of the parameters to determine material characterization is permittivity. Permittivity shows the ability of a material to store electrical energy that will interact with an electric field [2, 3]. The interaction between the electric field and the material can be observed based on perturbation theory where the energy stored in the material will perturb the electric field so that the resonance frequency will shift to a low frequency in line with an increase in the permittivity of the sample [4, 5].

Generally, the permittivity of samples is detected using commercial probe sensors, but they have limitations including complex structure, bulkiness, and low accuracy [6, 7]. Microwave sensors are one device that can be recommended for detecting the permittivity of samples [8, 9]. The advantages of microwave sensors include compact dimensions, high accuracy, and high sensitivity [10, 11]. Previous work proposed permittivity detection of solid samples using microwave sensors using Split Ring Resonator (SRR) [12], Dual Split Ring Resonator (D-SRR) [13], Complementary Split Ring Resonator (CSRR) [14], T-resonator [15], and interdigital structure (IDC) [16]. However, detection is currently proposed to be performed directly using a resonator, which means that it does not allow for reading detection with certain distance. Apart from that, the sensor proposed in previous work uses a resonator with two ports, so it cannot function as an antenna for transmitting electromagnetic waves. Moreover, tagging detection can also be proposed using Radio Frequency Identification (RFID) based approaches. RFID based permittivity sensor has the capability to detect permittivity of samples using horn antenna as interrogator. Generally, detection is determined based on Received Signal Strength Indication (RSSI) parameter of designed sensor which is connected with RFID reader to capture the interaction between sensor and sample [17–19]. However, the configuration of complex measurement equipment becomes limitation. In addition, detection result must be processed using RFID reader which has potential to produce high error rate. Therefore, microwave sensors that have detection capabilities at a certain distance are needed to support real-time and flexible measurements.

This work proposes an antenna sensor for permittivity detection of samples based on a close quarter approach. A microwave sensor is proposed based on a resonator with a single port operating at a frequency of 2.53 GHz with reflection coefficient $(S_{11}) \leq -10$ dB. Solid material samples are placed in the sensing area of the antenna sensor which is determined based on the electric field concentration. Furthermore, the interrogator antenna is proposed to detect permittivity with a certain distance (d) based on the frequency shift of the transmission coefficient parameters (S_{21}) of the antenna sensor.

The main contribution of this work is producing an antenna sensor that has the capability for tagging detection using a close quarter approach based on frequency shift for solid material

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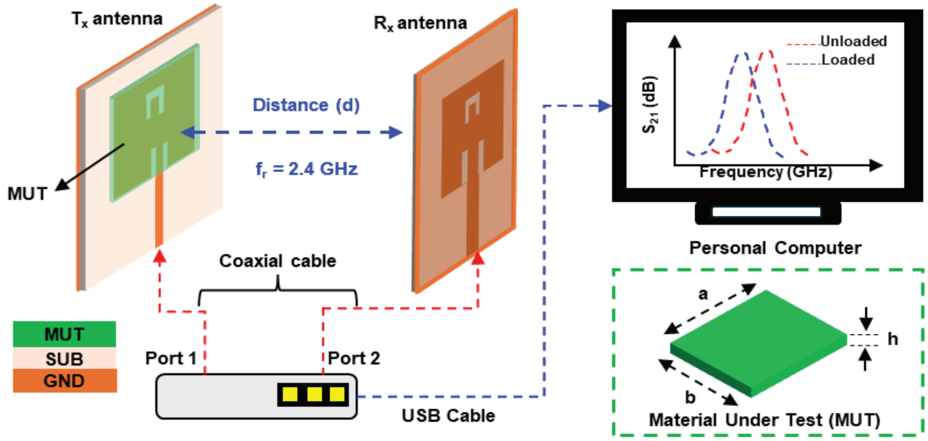

FIGURE 1. Proposed scenario for permittivity detection based on tagging antenna sensor.

characterization. Finally, this research can be recommended for permittivity detection in solid materials in real time for several applications including biomedical, pharmaceutical, and material quality control.

2. SCENARIO FOR CLOSE-QUARTERS PERMITTIVITY DETECTION BASED ON TAGGING ANTENNA SENSOR FOR SOLID MATERIALS

In this paper, the sensor antenna is designed to operate at a resonant frequency of 2.4 GHz using an FR-4 substrate with a permittivity of 4.3, a thickness of 1.6 mm, and a tan loss of 0.0265 [12]. Validation and verification of the proposed sensor is carried out using a Vector Network Analyzer (VNA) which is connected directly to the antenna using a coaxial cable and a computer using a USB cable. The sample used is solid which has certain dimensions with length, width, and thickness represented by a, b, and h. The sample is placed in the sensing area of the sensor antenna which is connected with port 1 of the VNA as the transmitter (Tx). Next, permittivity detection of the sample is proposed using an interrogator antenna connected to port 2 of the VNA as a receiver (Rx). The distance between Tx and Rx is determined based on the Fresnel region of the proposed antenna which is represented by $d = 2D^2/\lambda$. The scenario of close quarter detection using the proposed sensor antenna is shown in Figure 1.

Permittivity detection is observed based on the frequency shift and response of the transmission coefficient parameter (S_{21}) of the interrogator antenna. Based on perturbation theory, the frequency of the resonator shifts lower in line with increasing permittivity of the sample placed in the sensing area of the antenna sensor.

The sensing area is defined by the region with maximum electric field concentration, as indicated by the E-field distribution. Furthermore, the sample placed on the sensor antenna which functions as Tx will cause a frequency shift of the transmission coefficient on the interrogator antenna which functions as Rx. The correlation between frequency shift and permittivity change can be used to determine the permittivity of the sample using curve fitting based on polynomial equations.

3. METHOD

3.1. Development Model of Proposed Antenna Sensor

In this paper, the proposed antenna sensor is developed into three models represented by model 1, model 2, and model 3. Simulation and design of the sensor antenna are carried out using electromagnetic (EM) simulation with a resonance frequency of 2.4 GHz.

Model 1 is shown with a microstrip antenna with a rectangular patch connected to port 1 using a microstrip line. Furthermore, inset feed and inverted U-shaped slots are proposed to improve the performance of the antennas represented by model 2 and model 3. The overall model development and electric field concentration of the proposed sensor antenna are shown in Figure 2(a), Figure 2(b), and Figure 2(c).

Figure 2(a), Figure 2(b), and Figure 2(c) show that the proposed sensor antenna has a maximum electric field in the range of 0.05–1.75 kV/m at the center and edge of the patch at a resonance frequency of 2.4 GHz. Furthermore, the simulation results of S_{11} with the addition of an inset feed and an inverted U-shaped slot are shown in Figure 2(d). Based on the simulation results, the S_{11} of the proposed antenna with model 1 is still ≥ -10 dB, while for model 2 and model 3 antennas, it is ≤ -10 dB. These findings indicate that the addition of an inset feed and an inverted U-shaped slot successfully improves the performance of the S_{11} of the proposed antenna. In addition, the radiation pattern of the proposed antenna is shown in Figure 2(e) where model 3 has more optimal radiation than model 1 and model 2.

The dimensions of the sensor antenna are determined based on the resonant frequency and characteristics of the substrate used. The length and width of the antenna patch represented by W_p and L_p are determined based on the following equation [20]:

$$W_p = \frac{c}{2 f_o \sqrt{\frac{(\varepsilon_r + 1)}{2}}} \tag{1}$$

$$L_p = L_{eff} - \Delta_L \tag{2}$$

$$L_{eff} = \frac{c}{2 f_o \sqrt{\varepsilon_{eff}}} \tag{3}$$

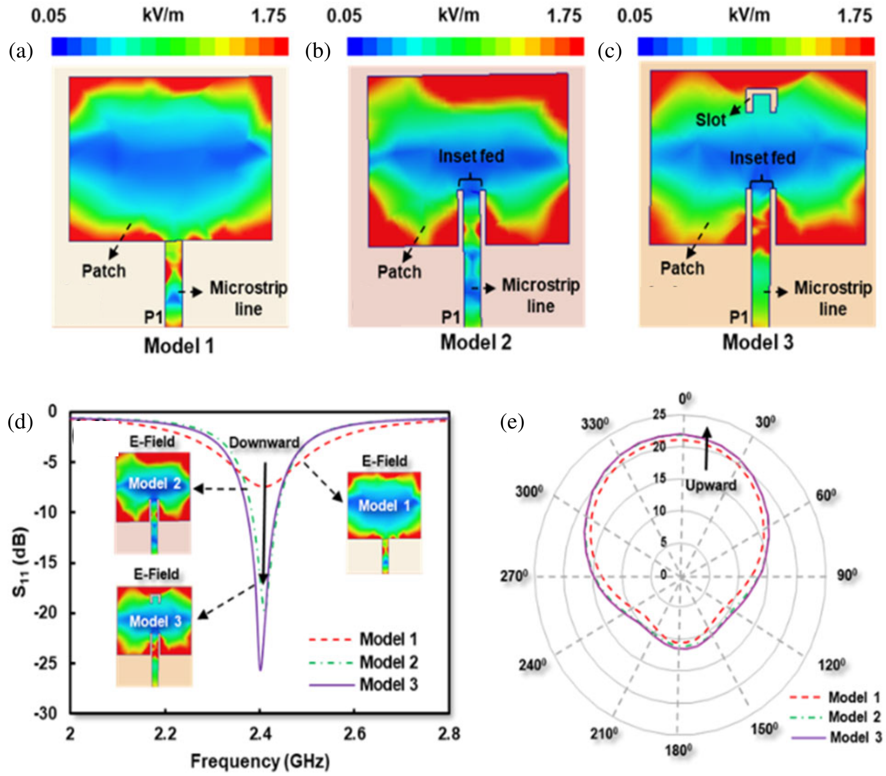

FIGURE 2. Development model and simulation result of proposed antenna at $f_r = 2.4$ GHz; (a) E-field for model 1, (b) E-field for model 2, (c) E-field for model 3, (d) simulation of S_{11}, (e) simulation of radiation pattern.

$$\varepsilon_{eff} = \frac{\varepsilon r+1}{2} + \frac{\varepsilon r-1}{2}\left[1+12\frac{h}{W_p}\right]^{-\frac{1}{2}} \tag{4}$$

$$\Delta_L = 0.412\frac{(\varepsilon_{reff}+0.3)\left(\frac{W_p}{h}+0.264\right)}{(\varepsilon_{reff}-0.258)\left(\frac{W_p}{h}+0.8\right)} \tag{5}$$

where W_p and L_p denote the patch's length and width, respectively; f_o stands for the resonance frequency; ε_r is the substrate's permittivity; ε_{eff} indicates the substrate's effective permittivity at a specific resonance frequency; h signifies the substrate's thickness; and ΔL accounts for the fringing field's edge effect on the patch.

Additionally, microstrip lines are suggested to regulate the antenna's impedance and reflection coefficient represented by W_z. The dimensions of the microstrip line are significantly affected by the input impedance and the chosen resonant frequency. In this study, the input impedance is set at 50 ohms. The dimensions of the microstrip line can be calculated using the following equation [21]:

$$W_z = \frac{2h}{\pi}\left\{B-1-\ln(2B-1)+\frac{\varepsilon_r-1}{2\varepsilon_r}\left[\ln(B-1)+0.39-\frac{0.61}{\varepsilon_r}\right]\right\} \tag{6}$$

$$B = \frac{60\pi^2}{Z_0\sqrt{\varepsilon_{eff}}} \tag{7}$$

In this context, W_z represents the width of the microstrip line, Z_0 the antenna impedance, and B the impedance constant. The antenna's impedance is set at 50 Ω, consistent with the impedance of the connector employed.

Additionally, the length of the microstrip line (L_z) is $^1/_4\lambda_g$, as determined by the following equation [22]:

$$L_z = {}^1/_4\lambda_g \tag{8}$$

$$\lambda_g = \frac{\lambda}{\varepsilon_{eff}} \tag{9}$$

Furthermore, S_{11} of the proposed sensor antenna was ≤ -10 dB as shown in Figure 3(a) while the structure of the antenna is shown in Figure 3(b). The overall dimensions of the sensor antenna structure are shown in Table 1.

3.2. Simulation of Permittivity Detection Using Antenna Sensor

The concentration of the E-field from the antenna sensor is at the edge and center of the patch, while the H-field is in the microstrip channel gap as shown in Figure 3(c) and Figure 3(d). However, the maximum concentration of the electric field is higher than the magnetic field so that the antenna characteristics are more capacitive. These findings indicate that areas with the highest E-field can be used as potential locations for sensing areas to detect the permittivity of samples. Figure 4(a) shows a scenario for tagging detection using the proposed antenna sensor where the Tx and Rx antennas are separated by a distance of $d = 10$ cm determined based on the Fresnel region

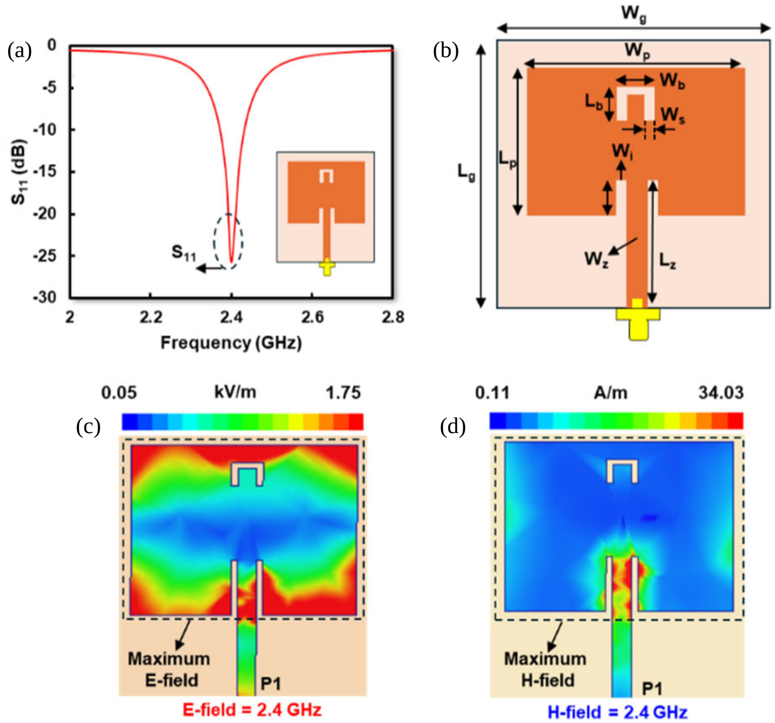

FIGURE 3. Simulation result and design of proposed antenna sensor; (a) S_{11}, (b) structure of proposed sensor, (c) E-field concentration at $f_r = 2.4\,\text{GHz}$, (d) H-field concentration at $f_r = 2.4\,\text{GHz}$.

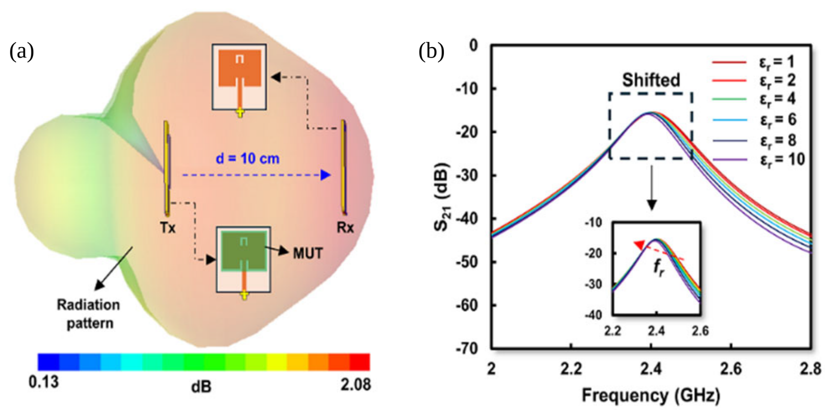

FIGURE 4. Simulation detection using antenna sensor; (a) tagging detection, (b) correlation between frequency and permittivity.

for a resonance frequency (f_r) of 2.4 GHz. Moreover, the permittivity of the sample placed on the T_x antenna is detected by the R_x antenna based on the frequency shift of the transmission coefficient (S_{21}) as shown in Figure 4(b). Based on the simulation results, the frequency of the antenna sensor shifts to low frequencies in line with increasing permittivity of the sample.

3.3. Simulation of Tan Delta Detection Using Proposed Sensor

Furthermore, the proposed sensor can also detect the change in dielectric losses of the sample based on the change in reflection coefficient (S_{21}) shown in Figure 5(a). The transmission coefficient of the proposed sensor moves to low along with the increase in dielectric loss of the sample in the range of 0–0.1. Based on simulation results, the transmission coefficient shifts from -15.45 dB to -15.55 dB for the tan delta range of 0–0.1 as shown in Figure 5(b). This finding indicates that the change in tan delta of the sample greatly affects the transmission coefficient of the proposed sensor.

3.4. Simulation of Permittivity Detection Using Antenna Sensor with d = 5 cm-10 cm

Furthermore, simulation with EM simulation is proposed to observe the performance of the proposed sensor against the distance between the sensor and the interrogator antenna represented by d for the range of 5 cm–15 cm as shown in Figure 6.

Based on the simulation results, the sensor can detect the permittivity of the sample for the distance range $d = 5$ cm–15 cm as shown in Figure 6(a), Figure 6(b), and Figure 6(c). Further-

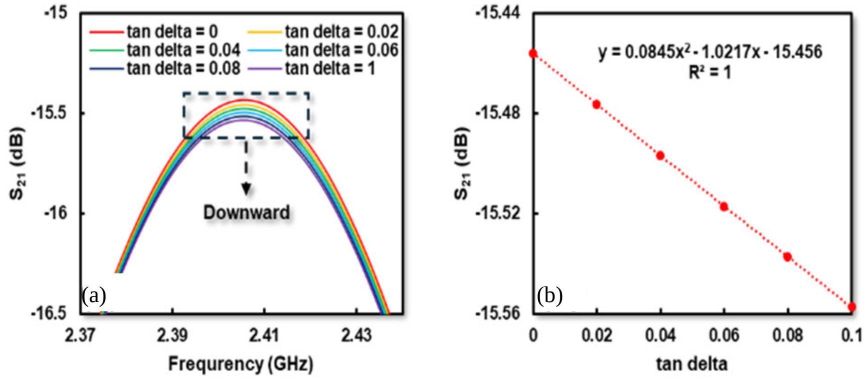

FIGURE 5. Simulation detection of tan delta with range of 0–0.1 using proposed sensor; (a) correlation resonance frequency with tan delta, (b) correlation between S_{21} and tan delta.

TABLE 1. Dimension of proposed antenna sensor.

Parameters	Dimension (mm)
W_g	50
L_g	50
W_p	36
L_p	28
W_z	3
L_z	15
W_b	5
L_b	4
W_i	1
L_i	9
W_s	1

more, the correlation of the resonance frequency and permittivity is shown in Figure 6(d) where the performance of the sensor is stable enough to detect the permittivity of the sample for the range $d = 5$ cm–10 cm. The simulation results show that the resonance frequency shifts from 2.408 GHz to 2.401 GHz for $d = 5$ cm while for $d = 10$ cm it shifts from 2.406 GHz to 2.398 GHz, and for $d = 15$ cm it shifts from 2.406 GHz to 2.397 GHz. Other findings show that the distance between the sensor and the interrogator antenna greatly affects the transmission coefficient (S_{21}) of the antenna where a long distance causes the transmission coefficient of the sensor to shift to low. The simulation results show that the S_{21} of the proposed sensor shifts from -9.45 dB to -15.41 dB and -20.99 dB for the distance range $d = 5$ cm–10 cm as shown in Figure 6(e). This finding indicates that the distance between the sensor and the interrogator antenna should be determined based on the fresnel region. Therefore, in this paper, the distance between the sensor and the antenna is determined based on the Fresnel region which is represented by $d = 2D^2/\lambda$.

4. RESULT AND DISCUSSION

4.1. Measurement and Verification

Measurements and verification of the proposed antenna sensor were carried out in the laboratory using a Vector Network Analyzer (VNA) with a frequency range of 2–2.8 GHz, a frequency step size of 0.001 GHz, and an ambient temperature of 25°C.

Measurement process for the permittivity detection of solid samples using VNA with a tagging antenna sensor is proposed where the two antennas are separated with a distance of $d = 10$ cm, and the sample is placed on the Tx antenna which is connected to port 1 while for the Rx antenna it is connected to port 2 as shown in Figure 7(a). In this experiment, four types of solid materials are proposed as samples as follows: polystyrene, polypropylene, polyvinyl chloride (PVC), and rubber. The permittivity of the sample was validated using a Keysight N1501A dielectric probe kit which was used as a reference to determine the permittivity of the sample using the proposed antenna sensor. The dimensions of the sample are adjusted to the location of the sensing area where the length, width, and thickness are $36\,\text{mm} \times 28\,\text{mm} \times 1\,\text{mm}$, respectively.

Furthermore, to ensure accurate sample placement, plastic clamps were used to attach the sample to the surface of the antenna sensor. A comparison of simulation and measurement results from the antenna sensor for S_{11} and S_{21} is shown in Figure 7(b).

Based on the measurement results, the sensor antenna experienced a frequency shift from 2.4 GHz to 2.53 GHz or a shift of 5.4%. This result is due to the uncertainty of the fabrication process and the permittivity range of the FR4 substrate where $\varepsilon_r = 4.3$–4.6. The correlation between the resonance frequency of the antenna sensor and changes in the permittivity of the sample is shown in Figure 7(c) where the resonance frequency shifts to a low frequency in line with the increase in the permittivity of the sample. The resonant frequency of the antenna sensor shifts from 2.534 GHz to 2.532 GHz for the four recommended samples with different permittivity as shown in Figure 7(d). In this experiment, the reference frequency used was the unloaded condition (vacuum). Next, the range of frequency shift of the antenna sensor represented by ΔF is determined based on the following equation:

$$\Delta F = f_{\text{unloaded}} - f_{\text{loaded}}\,(\text{GHz}) \tag{10}$$

where f_{unloaded} shows the frequency of the antenna sensor when there is no material, and f_{loaded} is the frequency when the sample is placed on the antenna sensor. Based on the calculation using Equation (10), the maximum ΔF for the proposed antenna sen-

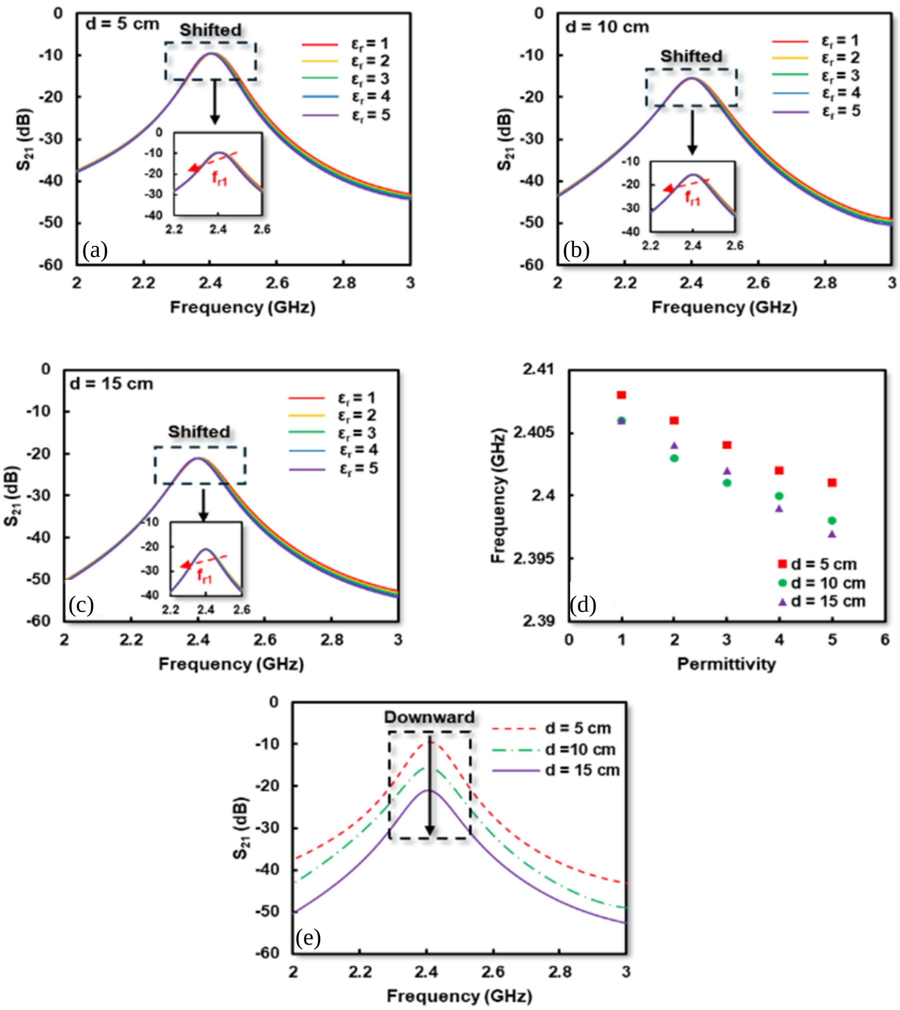

FIGURE 6. Simulation detection of tan delta with range of $d = 5$ cm–15 cm using proposed sensor; (a) $d = 5$ cm, (b) $d = 10$ cm, (c) $d = 15$ cm, (d) correlation between distance with resonance frequency and permittivity of samples, (e) correlation between distance and S_{21}.

sor is 0.012 GHz for the sample with the highest permittivity. Next, the permittivity of the sample is extracted based on fitting curve with a polynomial equation by observing the resonance frequency of the antenna sensor and the permittivity of the sample [23]. The correlation between the resonant frequency of the antenna and the permittivity of the sample is shown in Figure 8(a). Based on Figure 8(a), the correlation between permittivity and resonance frequency obtains a fitting curve with $R^2 = 0.98$. These results show that the obtained equation has high accuracy to determine the permittivity of samples. Furthermore, the permittivity of the sample can be determined using the following equation:

$$\varepsilon_r = 6823{f_r}^2 - 34750 f_r + 4426 \tag{11}$$

where ε_r is the permittivity of the sample, and f_r is the resonance frequency of the antenna sensor for four types of materials with different permittivities. The accuracy of permittivity detection using an antenna sensor and comparison with detection using a sensor probe are shown in Figure 8(b) and Table 2.

Table 2 shows that the proposed antenna sensor has high accuracy for permittivity detection of the four solid materials with a range of 91%–99%. Moreover, errors from measurement process arise from multiple sources, including calibration inaccuracies, environmental factors, and sensor design limitations. To minimize these errors, advanced calibration techniques, shielding from environmental interference, and improved sensor designs incorporating robust signal processing methods are essential.

In addition, the sensitivity (S) of the antenna sensor can be determined based on the following equation [23]:

$$S = \frac{\Delta F}{\Delta \varepsilon_r} \times 100\% = \frac{f_{\text{loaded}} - f_{\text{unloaded}}}{\varepsilon_r \text{samples} - \varepsilon_r \text{vacuum}} \times 100\% \tag{12}$$

where ΔF is the difference between the unloaded frequency and the loaded frequency of the sensor antenna for each sample, while $\Delta\varepsilon_r$ is the difference between the sample permittivity and the vacuum condition where $\varepsilon_r = 1$ as a reference. Based on the calculation results using Equation (12), the sensitivity of the proposed antenna sensor is 0.39% with a permittivity range of 1.02–4.12. Therefore, the proposed antenna sensor can be recommended for detecting the permittivity of solid materials with high accuracy.

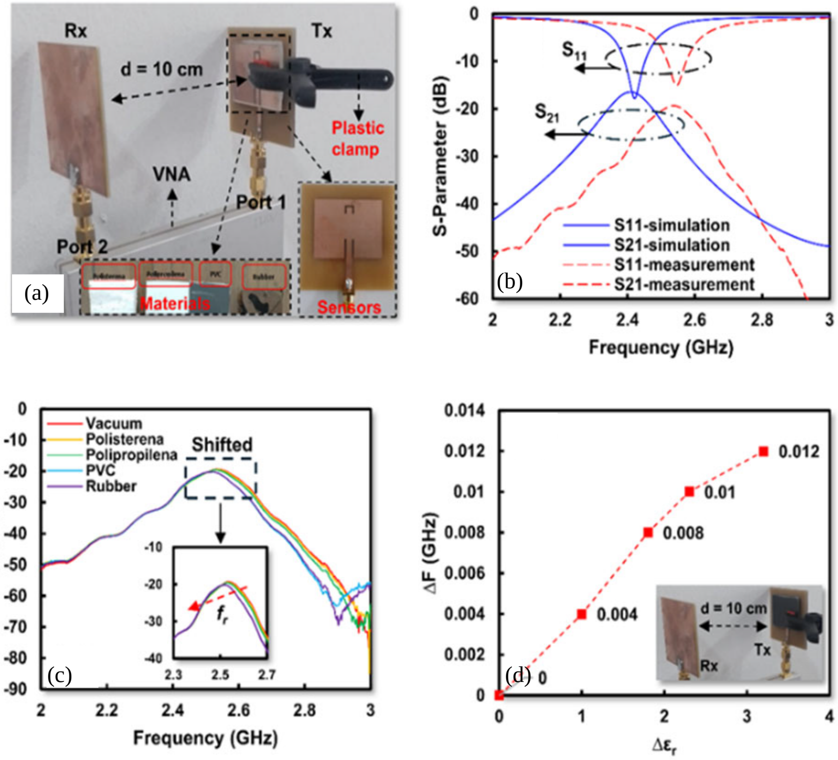

FIGURE 7. Measurement of proposed sensor; (a) setup for detection using tagging antenna sensor, (b) simulation and measurement result, (c) response of frequency with permittivity changes, (d) ΔF of proposed sensor.

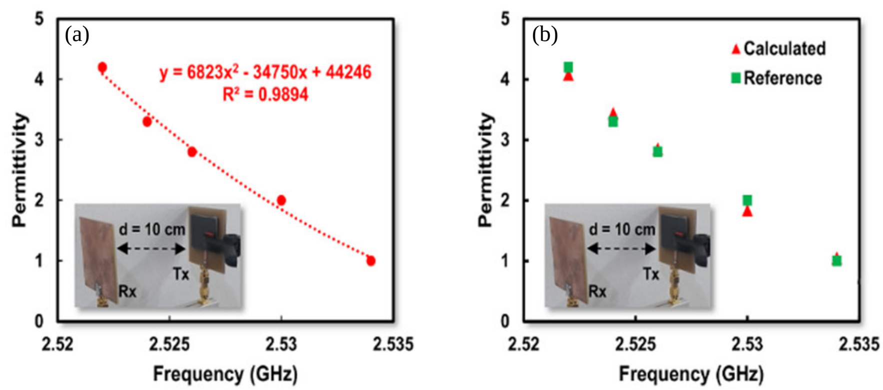

FIGURE 8. (a) Fitting curve for permittivity detection, (b) comparison permittivity from calculation and reference.

Furthermore, the validation of this work was carried out by comparing the performance of the proposed antenna sensor with the microwave sensor proposed in previous work as shown in Table 3. The performance of the sensors compared included resonance frequency, sample type, permittivity range, accuracy, sensitivity, and capability for tagging detection with a close quarter approach.

Previous work [13–16] proposed microwave sensors for permittivity detection of solid materials using dual SRR, nested SRR, T-ring resonator, and interdigital structure. However, the proposed work is not capable of tagging detection over a certain distance, and the structure is more complex to fabricate. Table 3 shows that the main contribution of this work is producing an antenna sensor that has the capability for tagging detection using a close quarter approach based on frequency shift for solid material characterization. Moreover, the proposed antenna sensor has a high accuracy of 96% for the permittivity range 1–4.13. However, the sensitivity of the antenna sensor is still small because the E-field is not optimally concentrated. Therefore, increasing the sensitivity of the antenna sensor can be recommended as further work such as combining the structure of single port resonator with interdigital capacitor (IDC) structures [24] or using artificial magnetic conductor (AMC) as sensing area with high concentrations of electric field [25]. Finally, the proposed tagging permittivity sensors have a wide range of real-world applications, particularly in material identi-

TABLE 2. Comparison measurements from antenna sensor and probe sensors.

Samples	Permittivity		Error (%)	Accuracy (%)
	Probe sensor	Antenna sensor		
Vacuum	1.05	1.02	2.7	97.31
Polystyrene	1.84	2.02	8.9	91.12
Polypropylene	2.85	2.82	1.1	98.85
PVC	3.44	3.32	3.6	96.38
Rubber	4.08	4.12	0.9	99.09

TABLE 3. Comparison of the proposed antenna sensor with existing works.

Ref.	Method	f_r (GHz)	Permittivity range	Samples	Sensing parameter	Sensing performance			Tagging detection	Close quarter approach	Design complexity
						ΔF (GHz)	Acc. (%)	Sens. (%)			
[13]	Dual SRR	2.27	1–4.3	Solid	Freq. shift	0.29	85%	8.52	No	No	Moderate
[14]	Nested CSRR	3.37	1–4.3	Solid	Freq. shift	0.47	87%	14.02	No	No	High
[15]	T-ring resonator	4.2	1–4.3	Solid	Freq. shift	0.18	95%	5.45	No	No	Moderate
[16]	Interdigital structure	5.65	1–4.3	Solid	Freq. shift	0.17	98%	3.25	No	No	High
This work	Antenna with U-slot	2.53	1–4.13	Solid	Freq. shift	0.012	96%	0.39	Yes	Yes	Low

fication, quality control, and environmental monitoring. These sensors utilize changes in permittivity to detect and differentiate materials in fields such as agriculture, food processing, and biomedical sensing. For instance, in agriculture, tagging permittivity sensors can monitor soil moisture content, ensuring optimal irrigation management. In the food industry, they help assess the freshness and composition of packaged goods by detecting changes in dielectric properties. In biomedical applications, these sensors can be integrated into wearable devices to monitor physiological parameters such as hydration levels and tissue properties.

5. CONCLUSION

This research has succeeded in designing and realizing an antenna sensor that operates at a resonant frequency of 2.53 GHz for permittivity detection of solid materials using a close quarter approach. Permittivity is detected based on the frequency shift of the transmission coefficient of the sensor antenna and interrogator antenna which are separated by a distance $(d) = 100\,\text{mm}$. The measurement results show that the antenna sensor has a high accuracy of 96% with a sensitivity of 0.39% and a ΔF of 0.012 GHz for a permittivity range of 1–4.13. These findings show that the proposed antenna sensor has high performance and can be recommended for real time measurements in the biomedical, pharmaceutical, and material quality control industries.

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