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The measurement of water level based on parallel-coupled lines with capacitance compensation

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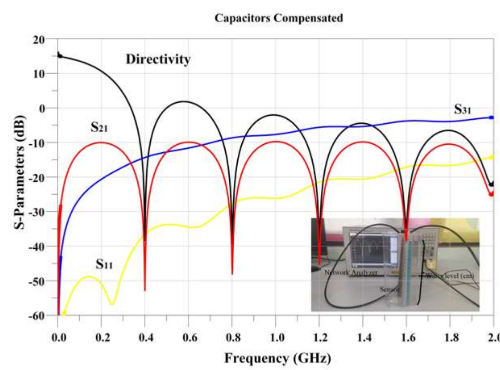
Abstract


This paper aimed to measure the water level using parallel-coupled microstrip lines with capacitor compensation. The design and implementation were parallel coupled microstrip lines with capacitor compensation to measure the water level. The technique of parallel-coupled microstrip lines had a coupling coefficient of – 10 dB. The center frequency was 200 MHz, and the compensated capacitor was positioned at ports 3 and 4. The water level was adjusted from 0 to 20 cm in the experiment. The frequency response of the coupling factor was measured from 300 kHz to 2 GHz. The coupling coefficient at 200 MHz was – 11.45 dB at 0 cm water level, where a shift of frequency decreased continuously. This technique was simple to follow, as the sensor was small and inexpensive.
Keywords: Water Level; Parallel-coupled Lines; Capacitance Compensation

1. Introduction

Currently, measurement and inspection of materials using electrical methods are popularly used. In the food and beverage industries, liquid sensors using capacitors have been applied for liquid level sensors [1, 2]. The use of metamaterial-based microstrip soil moisture sensors [3], interdigital capacitor water levels [4], and the passive element parallel-coupled lines [5], are easy to design and build. The parallel-coupled microstrip lines are part of a planar microwave sensor structure [6 – 8] that good convenience in the electronic circuit connection. The material qualification with electromagnetic (EM) has been used to measure liquid materials. A planar resonant RF sensor with the IDC technique employing non-contacting and non-destructive measurements was applied to find contamination in different oil concentrations [6]. In the research [7], a new technique to measure liquids, the ring resonator showed to protect the biological device or (to) control the environment [8]. This research presents a technique to increase the capacity of a microwave sensor with metamaterial coupling by measuring the water level for liquid qualification by using parallel-coupled microstrip lines. In [9 – 12] represented the use of parallel-coupled microstrip lines [10, 11], and the research found the qualification of the dielectric sample. In the work of [12], the technique to measure different water levels using parallel-coupled microstrip lines indicated the height S_{21}. However, the transfer line to build a parallel circuit of two-microstrip lines or up caused some unavoidable problems. Using the structure of dielectric material on the top and the dielectric at the bottom of the strip line in an inhomogeneous medium can speed up the phase of the couple line mode. Therefore, the parallel-coupled microstrip lines have a slower speed than the odd mode [13]. The mentioned research has not shown the use of parallel-coupled microstrip lines to measure water level by compensating the directivity referred from the technique of [13 – 17]. The compensation of the microwave sensor working process uses the design and the experiment would be referred from the work of [12] in this research.

In consequence, this article would like to solve the problems by compensating with capacitors connected at ports 3 and 4 of the parallel-coupled microstrip lines, as shown in Fig. 1. It shows the parallel-coupled microstrip lines, and Fig. 2 the compensation with capacitors. The design and the experiment were performed to measure the coupling coefficient – 10 dB, the center frequency at 200 MHz on the microwave FR4 substrate. In fabrication, a microwave sensor was formed to measure the water level. The structure was improved by connecting ports 3 and 4 to 50 Ω load then to the ground, as in Fig. 3(a). This method was referred to the work of [12], as shown in Fig. 3(b). This article presents are compensation with capacitors of the parallel-coupled microstrip lines, design, and fabrication of microwave sensor for level measurement, experiment and result, conclusion, suggestions, and acknowledgement.

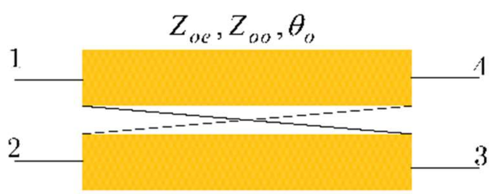


Fig. 1 The parallel-coupled microstrip lines.

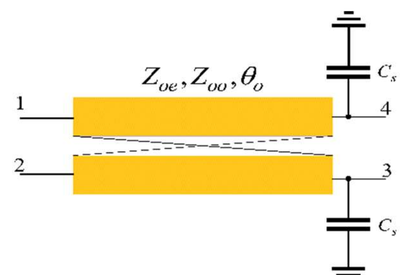


Fig. 2 The parallel-coupled microstrip lines compensated with capacitors.

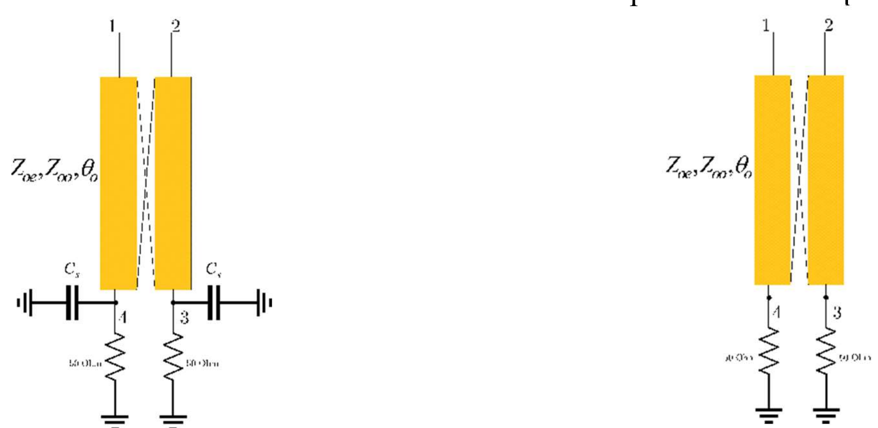


Fig. 3 The microwave sensor connecting to the parallel-coupled microstrip lines that are (a) compensated with capacitors to measure the water level and (b) non compensation.

2. Materials and Methods

The capacitors compensation of the parallel-coupled microstrip lines

As shown in Fig. 1, the parallel-coupled microstrip lines structure could be written as the simple characteristics impedance equations of even and odd modes (Z_{0e}, Z_{0o}) by Eq. (1) and (2) [5] respectively, where Z_0 is characteristics impedance 50 Ω, and C is a coupling coefficient, respectively.

$$Z_{0e} = Z_0\sqrt{\frac{1-C}{1+C}} \quad (1)$$

The even mode characteristics impedance.

$$Z_{0o} = Z_0\sqrt{\frac{1+C}{1-C}} \quad (2)$$

The characteristics impedance of Z_0 compute Z_{0e} and Z_{0o} is equal to

$$Z_0 = \sqrt{Z_{0e}Z_{0o}} \quad (3)$$

The capacitor compensation of the parallel-coupled microstrip lines at ports 3 and 4 is as shown in Fig. 2. Regarding the signal leak from the port of the parallel-coupled microstrip lines, it is composed of input, port 1; coupled, port 2; isolation, port 3; through, port 4. In Fig. 2, idealistically, the voltage from the isolation port has small values or is close to 0 (isolation zero). According to the electrical strength analysis by using the network theory, it established the equation that showed the voltage relationship at ports 1, 2, 3, and 4. The analysis of the four ports may be V_1, V_2, V_3, and V_4 as seen in Eq. (4 – 7) below.

$$V_1 = Z_{11}I_1 + Z_{12}I_2 + Z_{13}I_3 + Z_{14}I_4 \quad (4)$$

$$V_2 = Z_{21}I_1 + Z_{22}I_2 + Z_{23}I_3 + Z_{24}I_4 \quad (5)$$

$$V_3 = Z_{31}I_1 + Z_{32}I_2 + (Z_{33} + Z_{Cs})I_3 + Z_{34}I_3 \quad (6)$$

$$V_4 = Z_{41}I_1 + Z_{42}I_2 + Z_{43}I_3 + (Z_{44} + Z_{Cs})I_4 \quad (7)$$

Whereas Z_{Cs} is the impedance of the compensated capacitor at ports 3 and 4, the characteristics impedance of the parallel-coupled microstrip lines showed symmetry, and the results were $Z_{11} = Z_{22} = Z_{33} = Z_{44}$ $Z_{12} = Z_{22} = Z_{34} = Z_{43}$, $Z_{13} = Z_{31} = Z_{23} = Z_{42}$ and $Z_{14} = Z_{23} = Z_{32} = Z_{41}$. The techniques, according to [16, 17], changed from inductor to the capacitor. To find the default value of the compensated capacitors and the characteristics impedance of Z_{11}, Z_{12}, Z_{14} could be found from Eq. (4 – 7) and (8 – 11), respectively.

$$Z_{11} = \frac{1}{2}\left(Z_{0e}\coth\theta_e + Z_{0o}\coth\theta_o\right) \quad (8)$$

$$Z_{12} = \frac{1}{2}\left(Z_{0e}\coth\theta_e - Z_{0o}\coth\theta_o\right) \quad (9)$$

$$Z_{13} = \frac{1}{2}\left(Z_{0e}\operatorname{csch}\theta_e - Z_{0o}\operatorname{csch}\theta_o\right) \quad (10)$$

$$Z_{14} = \frac{1}{2}\left(Z_{0e}\operatorname{csch}\theta_e + Z_{0o}\operatorname{csch}\theta_o\right) \quad (11)$$

The relationship of S-parameter comprised the coupling coefficient or S_{21} and the capability of power transferring from port 1 to port 2, as seen in Eq. (12).

$$S_{21} = 20\log\frac{V_2}{V_1} \quad (12)$$

The isolation loss or S_{31} transferred voltage from port 1 to port 3, and when the result was close to zero, it affected directivity positively, as seen in Eq. (13).

$$S_{31} = 20\log\frac{V_3}{V_1} \quad (13)$$

When the values of the parallel-coupled microstrip lines were close to zero, the directivity (D) is related to S_{21} and S_{31}, as seen in Eq. (14).

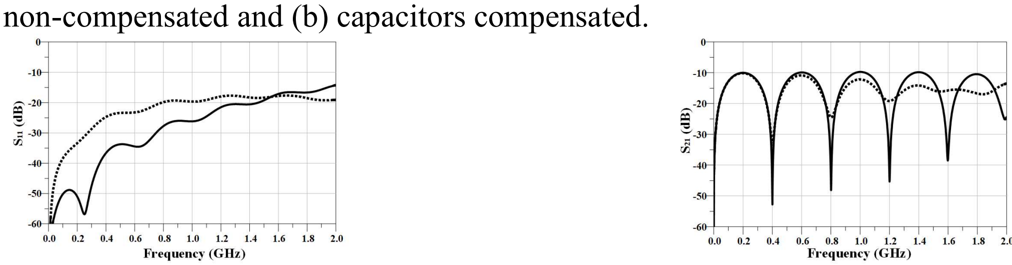
$$Directivity = 20\log\frac{V_3}{V_2} = S_{21} - S_{31} \quad (14)$$

Simulation capacitors compensation of the parallel-coupled microstrip lines

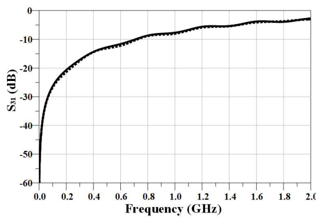
The simulation model using a computer program reflected the working process that affected the electromagnetic waves. In the analysis to find the frequency response using the momentum method, by setting the S_{21} at – 10 dB, the center frequency at 200 MHz on the FR4 substrate, the dielectric constant was 4.55, the height of the substrate was 1.6 mm, and loss tangent was 0.02. It resulted in characteristics impedance of even-odd mode according to the equations (1) and (2) or equal to Z_{0e}, Z_{0o} are 69.37, 36.03 Ω and the coefficient dielectric of even-odd mode ($\varepsilon_{effe}, \varepsilon_{effo}$) are 3.63, 2.84. The frequency response of the non-compensated parallel-coupled lines as in Fig. 4(a) demonstrates that the set 200 MHz of frequency caused the return loss or S_{11} (yellow line) of 33.37 dB; the S_{21} (red line) of – 10.16 dB; the S_{31} (blue line) of 21.37 dB; directivity (black line) of 11.21 dB, respectively. Regarding the parallel-coupled microstrip line capacitor compensated (as in Fig. 3(a)) to simulate the frequency response from the compensation at ports 3 and 4, C_s = 0.80 pF received from the processing to find the frequency at 200 MHz. The simulation showed that the return loss, or S_{11} of – 51.05 dB; the S_{21} of – 10.04 dB; the S_{31} of – 20.67 dB; the directivity is 10.63 dB are obtained as shown in Fig. 4(b). The comparison of the frequency response of the parallel-coupled microstrip lines, as seen in Fig. 5, the compensated capacitors (bold line) and the non-compensated (dash line). These represented the difference of the S_{11} according to Fig. 5(a). The presented technique decreased the loss return at 200 MHz of frequency lower – 33.37 dB, – 57.05 dB, at 600 MHz, a decrease of – 23.23 dB and – 34.49 dB, respectively. Fig. 5(b) compares the frequency response of the S_{21} at 200 MHz. This technique decreased the value from – 10.16 dB to – 10.04. At 600 MHz of frequency, it provided a better response, as S_{21} was over – 9.94 dB, the non-compensated version was – 10.89 dB. The capacitor compensation technique provided a better result for the frequency response at 1.80 GHz. In comparison, the S_{31} in Fig. 5(c), the results did not show a significant difference. Regarding the non-compensated technique with 200 MHz of frequency, the results were –20.67 dB and –21.37 dB, and for 600 MHz, the results were –11.63 and 12.19 dB. The difference did not show significance (nor directivity). However, when the frequency was increased, directivity has gradually decreases, as shown in Fig. 5(d). Consequently, the compensated capacitors could affect the S_{11} and the S_{21} of the parallel-coupled microstrip lines close to zero and give the transfer voltage from ports 1 to 2 with better efficiency. When applied this technique in the design and build of water level measurement (as seen in Fig. 3(a)) within the frequency range 200 kHz to 2 GHz, the research article showed the capacity of coupling factor from port 1 to 2, and the loss return, which can be discussed in the next topic.

(a) (b)

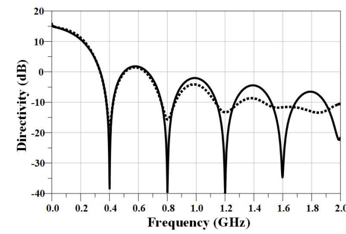
Fig. 4 Frequency response simulation of the parallel-coupled microstrip lines at 200 MHz to 2 GHz (a) non-compensated and (b) capacitors compensated.



(a) (b)



(c)



(d)

Fig. 5 Comparison of the frequency response of capacitors compensated and non – compensated.

Fabrication of Microwave Sensor for Water level measurement

For the design and fabrication of a microwave sensor based on parallel-coupled microstrip lines to measure the water level, the center frequency (f_0) at 200 MHz, and the S_{21} is – 10 dB, the synthetic to find the sensor is the size of the parallel-coupled microstrip line on FR4 substrate had electrical properties as follows, a dielectric coefficient at 4.55, 1.6 mm of the height, and a loss tangent at 0.02 resulting in characteristics impedance of the dielectric coefficients of even-odd modes as follows: 69.37, 36.03 Ω and 3.625, 2.836 Ω. The physical structure was composed of 2.38 mm of width (W), 0.35 mm of space (S), and 207.66 mm of length (L). The applied capacitors at ports 3 and 4 were synthesized by an open stub., where the physical structure of the microstrip radial stub had 2.6 mm of the width of the input line, 3.6 mm of the length of the stub, and 70 degrees of the angle subtended by stub as seen in Fig. 6. The physical structure and the simulation model of the circuit as shown in Table 1.

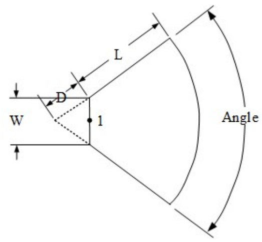


Fig. 6 The physical structure of the proposed microstrip radial stub.

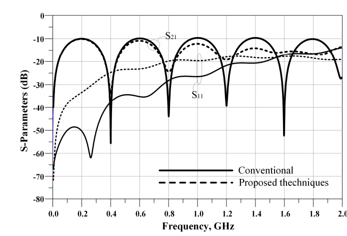


Fig. 7 Sensor simulation model of the parallel-coupled microstrip lines for liquid measurement.

Table 1 The physical dimension of the microwave sensor to measure water level.

Microwave Sensor	Non-compensated	Compensated
W, S, L (mm)	2.39, 0.35, 207.66 (mm)	2.39, 0.35, 200.20 (mm)
Microstrip Radial Stub W, L (mm) angle (°)	–	2.60, 3.67 (mm) and 70°

The simulation of the circuit and the impact of the electromagnetic wave using a computer program for analysis to find the frequency response of the microwave sensor from 200 kHz to 2 GHz. In the momentum method, the responsibility of the S_{21}, as seen in Fig. 7, demonstrated the frequency response of the S_{21} from port 1 to port 2; compared with conventional microwave sensors, the results showed the difference as aforementioned. The prototype of the microwave sensor measured the difference in water levels by observing the frequency response of the S_{21} and S_{11} only. As in Fig. 8, the sensor of the parallel-coupled microstrip lines had its sensor coated with an insulating substance to prevent it from having direct solution contact, which causes it to be an electrical conductor.

Experimental setup

The experiment tools were included E5063A ENA Series Network Analyzer, Keysight, the frequency range from the 100 kHz to 4.50 GHz, and the sample liquid was pure water. Before the experiment, the network analyzer was used to verify the correctness. The default setting of the frequency was 300 kHz – 2 GHz. The water level measurement was preceded by dipping the sensor into the sample water. The water volume was increased from 0 to 20 cm with the volume addition per once was 1 cm. Regarding the microwave sensor frequency response, the result from the record was processed by using the MATLAB program. It is presented into two parts, S_{21} and S_{11} of each height level, then find the water level affecting the S_{21}, and the S_{11}. Fig. 9 shows the sensor installation of the parallel-coupled microstrip lines made to measure water level and it recorded the frequency response as aforementioned

Fig. 8 The sensor model of the parallel-coupled microstrip lines for water level measurement.

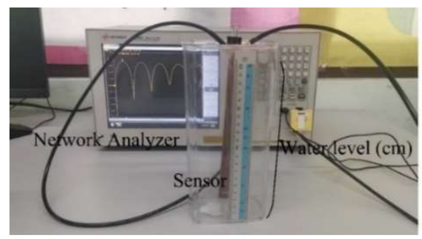


Fig. 9 The installation of the microwave sensor based on the parallel-coupled microstrip lines.

3. Results and Discussion

In the measurement results, Fig. 10 show that the S_{21} at 200 MHz of center frequency was – 11.45 dB at 0 (air) cm water level. The water level increase of rage between 1 cm to 20 cm measure have coupling, S_{21} from – 11.45, – 11.52, – 11.59, – 11.59, and – 11.60 dB respectively, as in section coupling (dB) @center frequency as Table 2. The measurement of the water level, the difference was observed. Regarding the 100 MHz frequency, as seen in Fig. 11. The measure of S_{21} increased to – 10 dB as aforementioned. The result of measurement of the S_{11} that the water level increase of rage between 1 cm to 20 cm measure have return loss as Fig. 12, the S_{11} from – 21.46, – 14.14, – 11.26, – 8.82, and – 7.01 dB respectively, as in section return loss (dB) @center frequency as Table 2.

Form Table 2, when considering the water level form 0 – 20 cm of the shifting center frequency from 200 reduce to 60.70 MHz, respectively. A second center frequency, the shifting center frequency, from 420 reduces to 121.40 MHz. The difference of frequency ($\Delta f = 2f_0 - f_0$), from 220 reduced to 60.68 MHz. Finally, the percentage of the relative difference of frequency ($\%\Delta$) reduced from 110% to 30.34%. In the experimental results, we would like to discuss the results as follows: the experiment to measure the S_{21} and water level, the sensor and the water level related with significance, and it could show the change of water level as in Table 2 ($\%\Delta$). However, the return loss is applied to distinguish water level at all. However, the proposed technique has its advantages and limitations. Table 3 is a comparison, respectively.

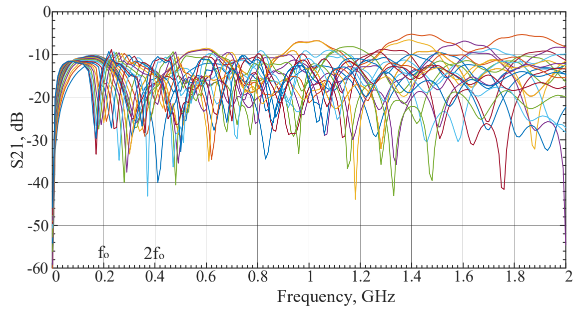


Fig. 10 Result of water level measurement S_{21} microwave sensor based on the parallel-coupled microstrip lines at a frequency between 300 kHz – 2 GHz.

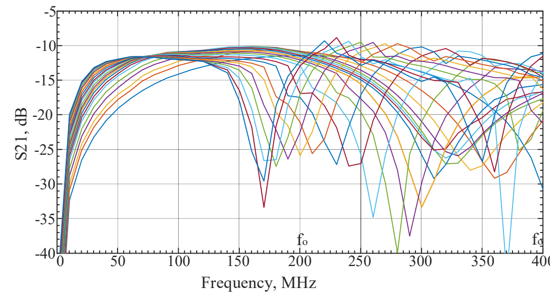


Fig. 11 Result of water level measurement S_{21} microwave sensor based on the parallel-coupled microstrip lines with a frequency between 300 kHz – 400 MHz.

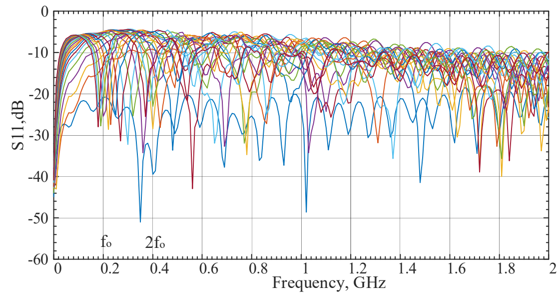


Fig. 12 Result of water level measurement S_{11} by the microwave sensor based on the parallel-coupled microstrip lines with a frequency between 300 KHz – 2GHz.

Table 2 The measurement microwave sensor based on the parallel-coupled microstrip lines at the water level.

Water level (cm)	**Coupling (dB)** @ f_0	**Return loss (dB)** @ f_0	f_0 **(MHz)**	$2f_0$ **(MHz)**	$\Delta f = 2f_0 - f_0$ **(MHz)**	$\%\Delta = \left(\frac{2f_0 - f_0}{f_0}\right)\times 100$
0	– 11.45	– 21.46	200	420	220	110
1	– 11.52	– 14.14	195.91	391.82	195.91	97.96
2	– 11.59	– 11.26	195.23	390.46	195.23	97.62
3	– 11.59	– 8.82	195.18	390.36	195.18	97.59
4	– 11.60	– 7.01	193.99	387.98	193.99	97
5	– 11.72	– 6.01	192.89	385.78	192.89	96.45
6	– 11.83	– 5.61	189.13	378.26	189.13	94.57
7	– 11.94	– 5.30	184.28	368.52	184.24	92.12
8	– 12.05	– 5.14	176.25	352.50	176.25	88.13

Table 2 The measurement microwave sensor based on the parallel-coupled microstrip lines at the water level (cont.).

Water level (cm)	Coupling (dB) @ f_0	Return loss (dB) @ f_0	f_0 (MHz)	$2f_0$ (MHz)	$\Delta f = 2f_0 - f_0$ (MHz)	$\%\Delta = \left(\frac{2f_0 - f_0}{f_0}\right) \times 100$
9	– 12.43	– 5.14	166.92	333.83	166.91	83.46
10	– 12.81	– 5.25	156.53	313.06	156.53	78.27
11	– 13.29	– 5.63	143.81	287.64	143.83	71.92
12	– 13.78	– 6.34	144.53	289.06	144.53	72.27
13	– 14.58	– 5.93	131.81	263.63	131.82	65.91
14	– 15.38	– 6.90	132.53	265.06	132.53	66.27
15	– 16.32	– 8.46	119.81	239.61	119.8	59.90
16	– 17.25	– 10.83	120.53	241.06	120.53	60.27
17	– 16.11	– 15.91	107.81	215.61	107.8	53.90
18	– 14.98	– 27.97	108.53	217.05	108.52	54.26
19	– 18.42	– 23.47	95.81	191.60	95.79	47.90
20	– 21.87	– 16.90	60.72	121.40	60.68	30.34

Table 3 Fabrication and comparison of capacitors compensation for microwave sensor based on parallel-coupled microstrip lines.

Ref.	Frequency (GHz)	Water level (cm)	Compensation	Fabrication
[12]	0.2	0 – 20	no	easy
[13]	3.9	NA	capacitor	complicated
[14]	12	NA	capacitor	complicated
[15]	0.2	NA	capacitor	complicated
This work	0.2	0 – 20 (1 cm)	capacitor	easy

4. Conclusion

The technique of parallel-coupled microstrip lines had a coupling coefficient of – 10 dB was applied in the experiment. The center frequency was 200 MHz, and the compensated capacitor was positioned at ports 3 and 4. The water level was adjusted from 0 to 20 cm range. The frequency response of the coupling coefficient was measured from 300 kHz to 2 GHz. The result obtained was – 11.45 dB at 0 cm water level, from which a shift of center frequency was a continuous decrease. This technique was a simple to follow, as the sensor was small and inexpensive cost. It is useful for food and beverage industry applications.

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