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Dual band, Miniaturized Permittivity Measurement Sensor with Negative-Order SIW Resonator

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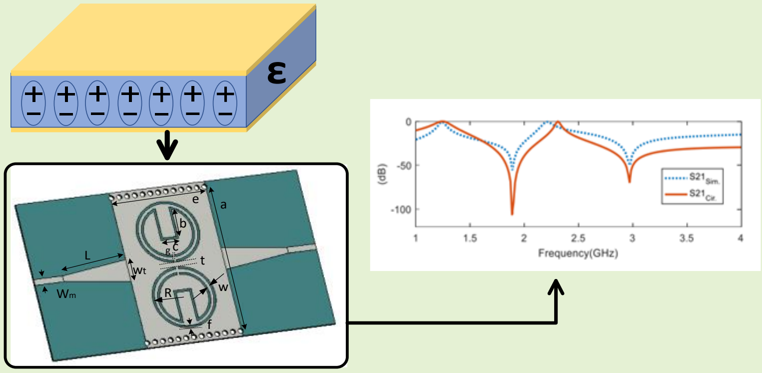
***Abstract*—A novel dual band, highly sensitive Substrate Integrated Waveguide (SIW) sensor for permittivity measurements is presented. A pair of modified Complementary Split Ring Resonators (CSRRs) is etched on SIW surface. CSRRs are located in the center of SIW, where the electric field distribution is high so that the coupling be maximized. The coupling between the SIW and the CSRRs as well as the adjacent CSRRs results in two notches in transmission coefficient. These notches vary with the dielectric loading on the sensor. The ratio of notch variation to the load permittivity variation determines the sensitivity of proposed sensor. Two sensitivities proportional to two notches are provided. Normalized sensitivities from both notches show identical values. Therefore, any environmental effect have the same impact on the TZs. This demonstrates the potential of the proposed sensor for differential operation that can mitigate the effect of environmental conditions. The size of the proposed sensor is small as the inductive and the capacitive effects of CSRRs forced the SIW to operate below the cut off frequency at negative-order-resonance mode. All design steps including SIW design, CSRRs design and modified CSRRs effects are presented in details. The sensor operation principle is described through its equivalent circuit model and simulation results. The experimental results indicates that the normalized sensitivity is 3.4%, which is much higher than similar sensors. The prototype sensor size (27.8×18.4×0.508 mm^3) is smaller than those reported in the literature.**



***Index Terms*—CSRR, highly sensitive, microwave sensor, small size, SIW.**

I. Introduction

NONE-DESTRUCTIVE characterization of material permittivity has many applications [1,2]. Microwave-based methods for non-destructive applications provide higher accuracy and real-time performance, which is an outstanding feature in comparison with other methods. Microwave sensors have excellent performance owing to design flexibility on Printed Circuit Board (PCB), easy fabrication, low cost as well as integration with other planar components. In available microwave sensors, the host consists of microstrip lines [3-5] or Substrate Integrated Waveguides (SIW) [6-7]. Usually Split Ring resonator (SRR) or Complementary Split Ring Resonator (CSRR) are loaded to the host and provide resonance condition, which leads to strong electric or magnetic fields concentrations around SRR or CSRR. Therefore, any variation in these fields, results in corresponding changes in resonant or transmission frequencies of these structures. SIW is a popular guided-wave structure due to high density integration with planar integrated circuits, high Q, low cost and low loss [8-9]. In [10], dielectric properties of substrate materials are characterized with modified SIW cavity. Enhanced SIW two-port sensor for material characterization is presented in [11], which shows low sensitivity due to limited penetration of electromagnetic field in material under test (MUT). An SIW temperature sensor for harsh environment and a tunable SIW sensor for liquid permittivity measurement are reported in [12] and [13], respectively. Hydrogen sensing based on SIW phase shifter [14] has a large operation frequency variation. Accurate permittivity estimation with a newly fed enhanced SIW sensor is achieved in [15]. CSRR is loaded on SIW for crack detection [16] and rotation measurement [17]. A dielectric permittivity detection sensor based on SIW with negative order resonance is reported in [18-19], which shows a significant level of miniaturization. Negative-Order-Resonance appears due to inductive and

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capacitive effects of CSRRs, where the SIW operates below the cutoff frequency of its equivalent waveguide. Therefore, operation frequency and transmission zeros are decreased. Generally decreasing the operation frequency, can be achieved by increasing the size of SIW, therefore size reduction is another result of CSRRs loaded on SIW, which will be explained in the next section. In most of available SIW sensors, the effect of CSRR on the size of the structure and also, dual band operation has not been investigated. In the proposed sensor, a novel SIW sensor loaded with modified CSRRs is presented. In order to minimize the size of sensor, CSRRs are loaded in the middle part of SIW, where the electric filed is maximum. The proposed design improves the sensitivity by extended CSRRs with rectangular split extension. This also provides dual band operation.

Microwave sensors are sensitive to change in surrounding conditions, since the electromagnetic propagation is also susceptible to permittivity change [21]. Dual band sensors can overcome this drawback. In dual resonant response for humidity elimination [22] two distinct resonators are implemented. One is constant to variation of MUT and the other is dynamic to MUT variation. However, the reported sensitivity is low. In [23] dual band operation is realized with two CSRRs, where variation in material properties affect both band resonators. This study did not address the environmental conditions. In [24] an attempt has been made to cancel temperature variations but the structures suffer from complexity caused by using two quarter ring resonator sensors. Dual notch microwave sensor based on complementary resonator for permittivity detection is reported in [25]. Differential operation is also investigated in dual band sensors [26-27]. In [25] two microstrip line is loaded with CSRRs. Symmetrical loading results in a single band stop notch in the transmission response, whereas asymmetrical loadings lead to double notches. The sensitivity of this sensor is influenced by the length of transmission line. A similar study is designed in [26] for microfluidic sensitivity. In [27] step impedance resonators (SIPs) are used, however, the inductance between two SIRs affects the sensitivity.

In the proposed sensor the theoretical sensitivity of two bands is identical. Therefore, variations in surrounding condition leads to similar changes in sensitivities. It shows the potential of the proposed sensor for operation in differential mode that can eliminate the environmental effects. In this sensor, an SIW at ISM (Industrial Scientific and Medical) band is designed as a transmission line. The CSRRs are etched on top wall of SIW, that results in Transmission Zero (TZ) on transmission coefficient as well as size reduction. Therefore, loaded SIW operates below the characteristic cut off frequency of equivalent waveguide in evanescent mode. Finally, rectangular extension is connected to inner slot of CSRR. Therefore, the total slot length is increased and dual band operation is realized. The operation principle of the proposed sensor is based on TZs changes due to loading with MUT. The major points of the presented sensor can be summarized as follows:

- Dual band operation with one sensing area and with modified CSRRs
- The equal normalized theoretical sensitivity for both bands
- Compact size, because of inductive and capacitive effects of CSRRs loaded on empty space in top side of SIW
- High sensitivity due to increasing the electrical length of CSRRs with rectangular slot
- The easily integration with other planar components outcome of using SIW as host transmission line

The paper is organized as follows: design of SIW resonator is presented in details in Section II. Equivalent circuit model and sensitivity analysis is formulated as well. Section III presents measurement results and performance comparison with similar designs reported in the literature. Finally, section IV draws some conclusions.

II. DESIGN AND OPERATION PRINCIPLE

The configuration of the proposed sensor including an SIW and two CSRRs as host transmission line and sensing area are shown in Fig. 1. The electric field has maximum value in middle part of SIW according to waveguide operation principle [28]. Therefore, CSRRs are located in middle part of SIW, so that any perturbation in electric fields distribution leads to change in operation frequency and transmission zeros of the sensor. Loading the SIW with CSRRs results in a notch on transmission coefficient due to capacitive and inductive effects of CSRRs. A split rectangular slot inside the CSRRs generates second transmission zero that leads to dual notch behavior of the sensor. In the proposed sensor, size minimization is the motivation for using CSRRs on top of SIW, as one sensing area for dual band operation while two sensing parts are used in similar sensors. On the other hand, high sensitivity to permittivity can be achieved by extending the electrical length of CSRRs in rectangular form.

A. Design Procedure

SIW is realized with two rows of metallic vias on PCB. In the proposed sensor an SIW for operation in ISM band on RO4003 with $\epsilon_r = 3.55,\ tan\delta = 0.0027,\ h = 0.508$mm has been designed. The width of SIW found as in [29-30]:

$$W_{SIW} = W + \frac{d^2}{0.95P} \tag{1}$$

$$f_{c10} = \frac{1}{2W\sqrt{\mu\varepsilon}} \tag{2}$$

where d is the diameter of the vias, P is the pitch between adjacent vias, and W is the width of the equivalent rectangular waveguide. The values of d and P are set to minimize radiation loss as well as return loss. For an electrically small post $d < 0.2\lambda_{gSIW}$ minimum radiation loss is achieved. With $\frac{d}{P} \geq 0.5$ and $\frac{d}{W_{SIW}} < 0.4$ the SIW can perfectly map to equivalent rectangular waveguide [30]. For the proposed sensor P=1 mm, d=1.5 mm, $f_{c10} = 2.7\ GHz$ are selected and $W_{SIW} = 27.8\ mm$ is found from (1) and (2).

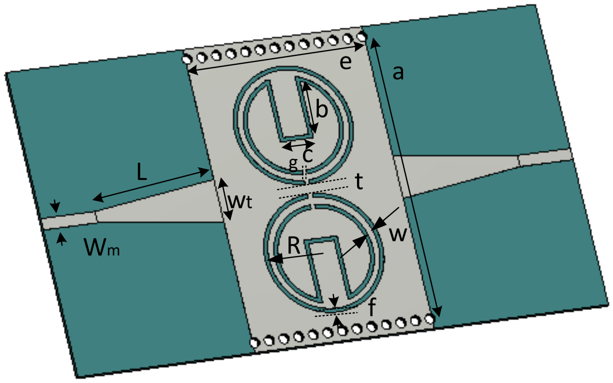
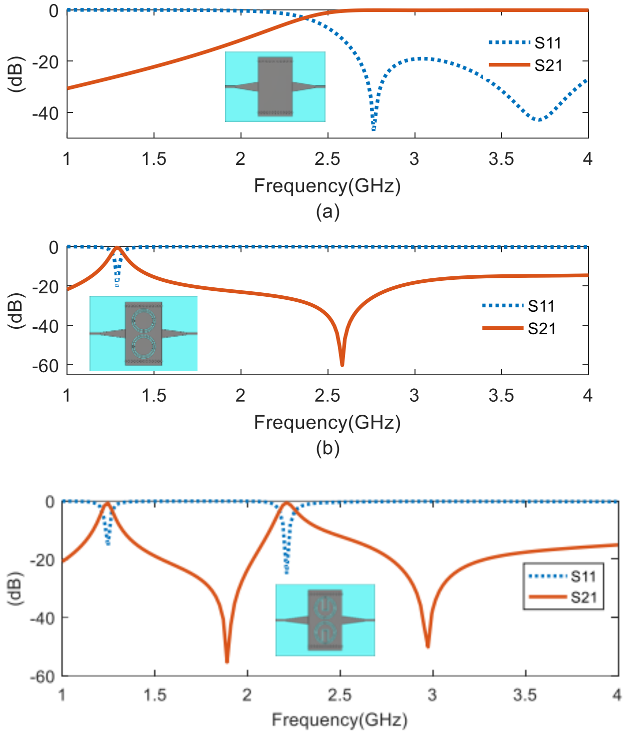


Fig. 1. The proposed sensor configuration, a=27.8mm, b=4.77mm, c=3.41mm, f=0.4mm, e=18.4mm, L=12.5, w=0.6mm, Wt=4.35mm, Wm=1.1mm, g=0.45mm, t=1mm, R=6mm.

The simulation result of the SIW is shown in Fig. 2 (a). Two sub wavelength CSRRs are aligned in the center of SIW in order to provide strong coupling between SIW and CSRRs [31] as the electric filed reaches maximum values in the waveguide center [32]. Fig. 2 (b) shows the simulation result of the loaded SIW. SIW was operating below the cut-off frequency [33] therefore operation frequency was shifted to a lower frequency at 1.2975 GHz. The miniaturization factor for the proposed SIW can be calculated as following.

$$M.F.=\frac{A_{SIW,f0}-A}{A_{SIW,f0}}\times 100 \qquad (3)$$

Where $A_{SIW,f0}$ and A are the area of conventional SIW at operation frequency of f_0 and the area of the proposed SIW loaded with CSRRs, respectively. The width of the SIW for the operation frequency of 1.2975 GHz is 61.36 mm according to (1) and for the proposed sensor in Fig.2 (b) is 27.8mm. Miniaturization factor is about 54.7% for the proposed sensor (3). Moreover, the first TZ is appeared according to Fig. 2 (b). The CSRRs can be viewed as electric dipole [34] and behave as electric scatterers. Therefore, CSRRs are capable of generating a stop band [35-36] and also evanescent-wave transmission. Split rectangular ring is connected to the inner ring of CSRR so, the electrical length of the proposed CSRR is longer than conventional CSRR. Therefore, the current passing through the gaps experiences an extra inductance. Consequently, another TZ is appeared, and also the first TZ is changed. Finally dual notch SIW sensor at 1.888GHz and 2.983GHz frequencies is achieved as shown in Fig. 2 (c). The effects of two geometrical parameters on the TZs locations are studied. The different length values of rectangular split ring (b) and gap of CSRRs (g) are examined, and the simulation results are shown in Fig. 3 and Fig. 4, respectively. By increasing the length of rectangular split ring (b) higher TZ frequency shifts up (Fig. 3(a)) whereas the lower TZ frequency shifts down (Fig. 3(b)). Fig. (2) shows that by increasing the length of rectangular split ring the electrical length and consequently the inductance effect due to lower TZ increases therefore, TZ becomes smaller. For the higher TZ by decreasing the corresponding electrical length, inductive effect decreases and TZ is growing. Increasing the gap (g) in the proposed sensor leads to increasing the higher and lower TZs according to Fig. 4. The simulation results in Fig.3 and Fig. 4 show that with these two parameters the TZs of the proposed sensor can be adjusted for desired band, and also dual notch operation is carried out, without changing the size of the structure.



(c)

Fig. 2. The simulation results of (a) SIW (b) SIW loaded with CSRRs (c) SIW dual notch sensor.

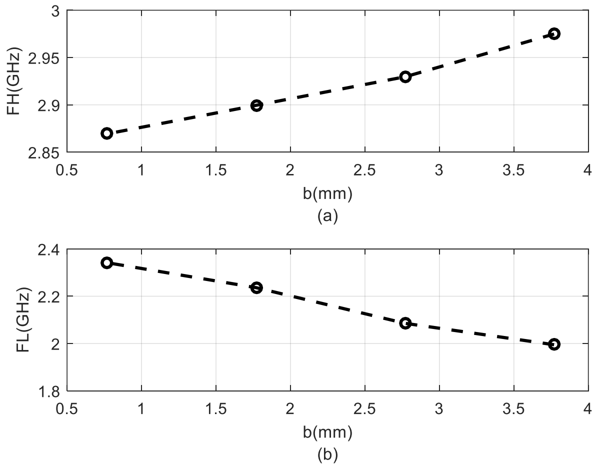


Fig. 3. The effect of rectangular split ring length on (a) high TZ (b) low TZ

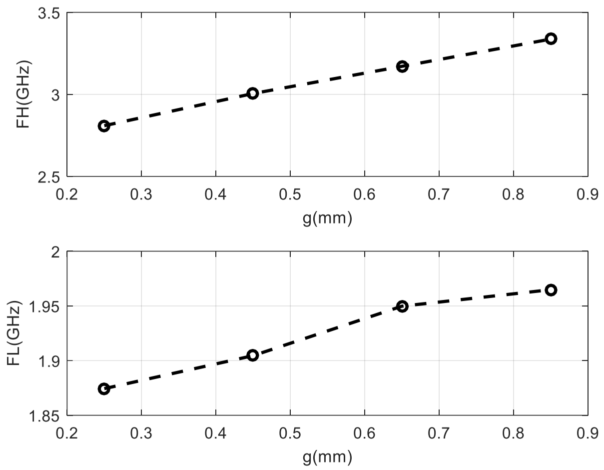


Fig. 4. The effect of gap on (a) high TZ (b) low TZ

B. Equivalent Circuit Model

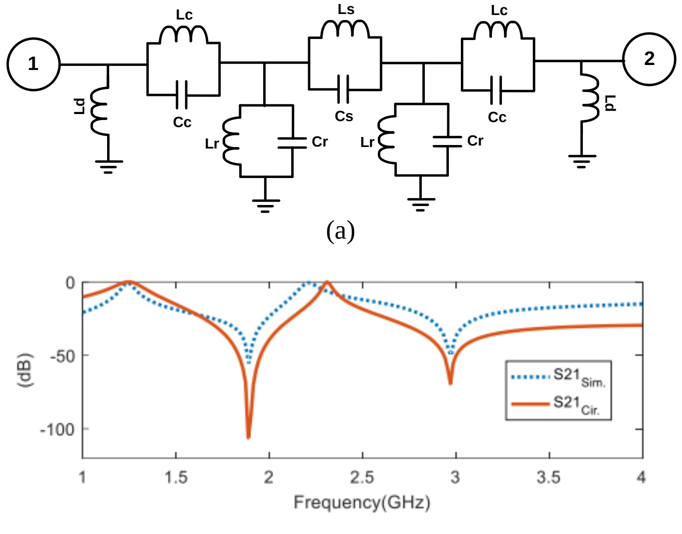
The equivalent circuit model of the proposed sensor is derived for design purposes as shown in Fig. 5(a) [27]. The simulation results in Fig. 5(b) possesses two TZs and two poles. The first TZ is created from coupling between SIW and CSRRs. The second TZ is related to mutual coupling between modified CSRRs. The metalized via and CSRRs are modeled as L_d and shunt connected resonator tank formed by capacitance C_r and inductance L_r respectively. Inductive connection through the split of rings between the SIW and resonators, is shown with L_c. The capacitive coupling between the SIW and CSRRs is denoted by C_c. The magnetic and electric coupling between CSRRs is described by parallel combination of L_s and C_s. This circuit model is a simple version and it is valid for a restricted frequency range. The electrical parameters of the proposed model are, $L_d = 13.544$ nH, $L_c = 2.9155$ nH, $C_c = 2.44$ pF, $L_s = 0.5$ nH, $C_s = 5.75$ pF, $L_r = 2.1695$ nH, $C_r = 9.012$ pF. The equivalent circuit model gives first TZ at:

$$f_{ZL} = \frac{1}{2\pi\sqrt{L_c C_c}} \tag{4}$$

The second TZ is raised from coupling between CSRRs and it is given with:

$$f_{ZH} = \frac{1}{2\pi\sqrt{L_s C_s}} \tag{5}$$

Therefore, the initial values of circuit parameters (L_c, C_c, L_s, C_s) find from (4) and (5). The shunt connected resonator tank (L_r, C_r) create poles in transmission coefficient (Fig. 5(b)), so L_r *and* C_r extract from pole values. The extracted initial values for the equivalent circuit with the mentioned methodology are optimized in ADS software. In order to verify the circuit model, the simulation result of circuit and electromagnetic model are compared in Fig. 5 (b). Despite a small frequency shift in the second transmission pole, there is a good agreement between the results.



(a)

(b)

Fig. 5. (a) The equivalent circuit model. (b) the simulation results of the equivalent circuit model, and the electromagnetic model.

C. Sensitivity Analysis

The theoretical sensitivity analysis of the proposed sensor is carried out based on the simulation results of MUT for different permittivity values. In simulations, a glass with the size of 24×50× 0.13 mm^3 lies on the top of the CSRRs so that it covers CSRRs completely. The permittivity of cover glass ϵ_r is varied from 1 to 10 with steps of 1 in the simulation and TZs are recorded. Polynomial curve fitting model [37] is used for formulating, explicitly, the dependency of high and low TZs on the permittivity of MUT as shown in (6). The polynomial coefficients are listed in Table I.

$$f_{Zi} = \mathrm{a}_i \times 10^{-4}{\epsilon_r}^4 + \mathrm{b}_i \times 10^{-3}{\epsilon_r}^3 + \mathrm{c}_i \times 10^{-2}{\epsilon_r}^2 + \mathrm{d}_i \times 10^{-1}\epsilon_r + e_i \qquad i = H, L \tag{6}$$

TABLE I

Polynomial Model Coefficients

i	a_i	b_i	c_i	d_i	e_i
H	1.001	−2.94	3.428	−2.534	3.202
L	-0.537	1.659	1.980	-1.514	2.022

H=Higher L=Lower

The theoretical sensitivity is also derived from (7) [37].

$$S = \frac{\partial f_z}{f_o \partial \epsilon_r} \times 100 \tag{7}$$

Where f_z is the TZ and f_o is the TZ of the empty sensor, and ϵ_r is the relative permittivity of the load. High and low transmission zeros variation in terms of permittivity are shown in Fig. 7 (a) and (b) respectively. Higher transmission zeros show 825 MHz changes while low transmission zeros show 522 MHz changes for the same permittivity variation. The normalized sensitivity for low and high TZs is 3.1%. Therefore, any environmental conditions have the same effect on the sensitivity. The sensitivity variation in terms of the sample permittivity's is shown in Fig. 8(a) and Fig. 8(b) for high and low TZs respectively. It shows that by increasing the permittivity, the sensitivity is decreased generally.

D. Thickness and Lift-off Analysis

The shift in transmission zeros of the proposed sensor can be explained as the interaction between fringing electric field of the CSRRs with the dielectric samples. This near field phenomenon is limited to very close proximities to CSRRs. The sample dimensions are selected so that, it covers whole CSRRs area and the sensitivity to position of samples is removed. However, the sensor is sensitive to thickness of the samples. In order to eliminate thickness effect, thick enough samples are used. In thin samples fringing fields are confined inside the sample volume. The minimum thickness which is enough for ignoring, the thickness effects is 1.4mm which, is find with simulation of a sample for different thicknesses [4]. In the proposed design, the fringing field decreases with increasing vertical distance. The simulation results show that the maximum lift-off distance is 0.6 mm and 0.4 mm for high and low TZs, respectively.

III. EXPERIMENTAL RESULTS

A prototype of the proposed sensor, is made and the measurement setup for permittivity characterization is provided. The measurement results including the TZs variation are used for experimental sensitivity computation.

A. Measurement Results

A prototype of the proposed SIW sensor is fabricated on RO4003 substrate. The measurement setup and fabricated SIW sensor are shown in Fig. 6. It includes the fabricated sensor, two clamps with plastic screws, an unmetallized PCB, and test samples. The sample under test is placed on top of the sensor. A piece of unmetallized PCB is placed under the sensor, and two clamps are holding the sample under test between its screws and sensor. The clamps keep the dielectric test samples in its position and push it against the substrate to achieve more accurate results. The test samples in rectangular shape with dimension of 20×30 mm^2 are cut from unmetallized microwave substrates. The size of the samples is adjusted for completely covering the sensing area of the sensor (CSRRs). The thickness of the samples is larger than 1.2 mm to neutralize the thickness effect on TZs of proposed sensor. Test samples are RT Duroid 5870($\epsilon_r = 2.33$ $h = 1.575$mm), FR4($\epsilon_r = 4.3$ $h = 1.6$ mm), RT Duroid 6006($\epsilon_r = 6$ $h = 1.905$ mm), RT Duroid 6010($\epsilon_r = 10.22$ $h = 1.9$ mm). The measured high and low TZs are summarized in TABLE II.

TABLE II
MEASUREMENT RESULTS FOR DIFFERENT SAMPLES

Sample	ϵ_r	High TZs(GHz)	Low TZs(GHz)
RT 5870	2.33	2.095	1.405
FR4	1.6	2.425	1.600
RT 6006	6	2.545	1.675
RT 6010	10.22	2.740	1.795
Bare	1	2.965	1.930

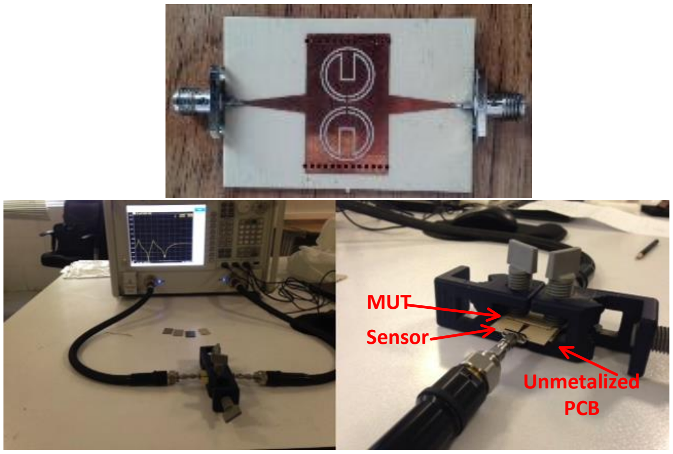


Fig. 6. The measurement setup and fabricated SIW sensor.

Measurement results for high and low TZs are shown in Fig. 7(a) and Fig. 7(b) respectively. The high frequency variation (645 MHz) is larger than low frequency (390 MHz) variation for the same permittivity difference, which is close agreement with simulation results. Polynomial curve fitting model are applied on the data in TABLE II [37] for obtaining the dependency of high and low TZs to permittivity of MUT as shown in (8) and TABLE III. The experimental sensitivity for high and low transmission zeros is extracted and shown in Fig. 8 (a) and (b) separately. Examining Fig. 8 reveals that sensitivity follows a similar trend.

$$f_{Zi} = \mathrm{a}_i \times 10^{-3}\epsilon_r{}^3 + \mathrm{b}_i \times 10^{-2}\epsilon_r{}^2 + \mathrm{c}_i \times 10^{-1}\epsilon_R + +d_i \qquad i = H, L \tag{8}$$

TABLE III
Polynomial Model Coefficients

i	a_i	b_i	c_i	d_i
H	−7.846	1.837	−2.093	3.152
L	-6.194	1.331	-1.345	2.050

H=Higher L=Lower

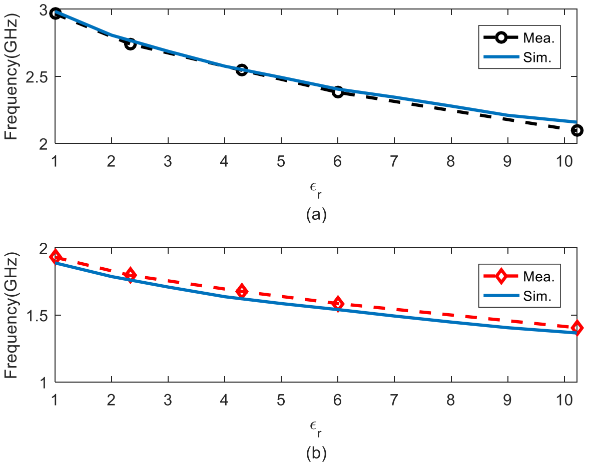
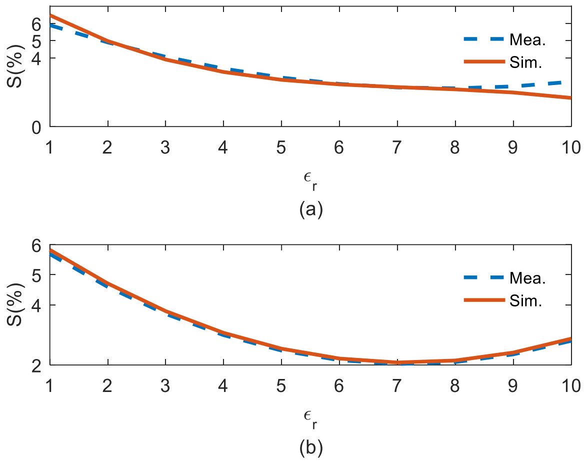


Fig. 7. Measured and simulation transmission zeros as a function of permittivity for (a) high TZ (b) low TZ



(a)

(b)

Fig. 8 Measured and simulation sensitivity as a function of loaded sample permittivity (a) Higher TZ (b) Lower TZ

TABLE IV
COMPARISON OF THE PROPOSED SENSOR WITH OTHER SENSORS

Ref.	$f_0\ (GHz)$ Upper	Lowe	$\frac{\Delta f}{\Delta \epsilon_r}(MHz)$	S (%)	$A_{SIW}\ (\lambda_g{}^2)$	Material type	R.P	Sensor Type
[6]	5.831(5.812-5.850)	-	0.6	1.03×10^{-2}	0.51	Liquid	8-70	Slot in SIW
[11]	2.455(2.391-2.519)	-	1.77	7.2×10^{-2}	0.25	Liquid	5.25-77.5	Hole in SIW
[18]	2.674(2.673-2.677)	-	0.63	2.7×10^{-3}	0.214	Liquid	4.78-39.19	I.C in SIW
[15]	2.977(2.897-3.058)	-	20.18	0.67	0.23	Solid	2.1-10.2	Slot in SIW
[38]	2.5	-	-	0.27	0.07	Liquid	1-140	SRR
Proposed	2.4175(2.095-2.740)	1.6(1.405-1.795)	49.43-81.75	3.4-3.1	0.05-0.1	Solid	2.33-10.22	CSRRs in SIW

R.P=Range of permittivity in measurement, I.C=Interdigital Capacitance

The measurement results in TABLE II are used for comparing the proposed sensor with similar structures. Most of the selected designs in TABLE IV have made on SIW technology. To make more inclusive comparison some sensors which are made with microstrip and SRR are investigated. SRR in folded form for liquid characterization [38] and in parallel form for monitoring the flowing fluids inside a capillary [39] are used. Non-invasive glucose sensing in aqueous solution with an active SRR is also reported [40]. For having the reasonable comparison, the normalized sensitivity is used as follows.

$$S = \frac{1}{f_o}\frac{\Delta f}{\Delta \epsilon_r} \times 100 \tag{9}$$

$$f_0 = \frac{f_{01} + f_{02}}{2} \qquad \Delta f = f_{o2} - f_{o1} \tag{10}$$

where f_{o1} and f_{o2} are upper and lower frequencies in detection frequency domain, respectively. The size of SIW part of the sensor without microstrip transition part is shown with A_{SIW}. Therefore, the size reduction effect due to inductive and capacitive effects of CSRRs is included. By considering the different operation frequency of the sensors, its size must be normalized for fair comparison. So, $A_{SIW}\ (\lambda_g{}^2)$ (the normalized size to guided wavelength of SIW) is shown in TABLE IV. The guided wavelength for equivalent rectangular waveguide is given by:

$$\lambda_g = \frac{\lambda}{\sqrt{1 - (\frac{f_c}{f_o})^2}} \tag{11}$$

Where f_c and f_o are given in (2) and (10) respectively and λ is the operation wavelength. Normalized size of the proposed sensor is 0.05 and 0.1 with respect to high and low TZs respectively. Comparison table shows that the size of the proposed sensor is at least 4 times less than similar SIW sensor in high TZ and close to [38]. Moreover, the normalized sensitivity is 3.4 and 3.1 percent for high and low TZs respectively. These sensitivity values are close and confirms the differential mode operation of proposed sensor. The normalized sensitivity of proposed sensor is 5 times greater than the best of the similar sensors. Range of permittivity for liquid MUT is higher than solid MUT.

IV. CONCLUSION

A new SIW based sensor for material characterization is proposed. SIW and CSRRs are used as host and sensing area respectively. CSRRs are etched on middle part of SIW surface, to reach extreme coupling. The proposed sensor operates bellow cut off frequency and has two TZs. Experimental results show 3.4% and 3.1% normalized sensitivity for high and low TZs respectively. The normalized size of the SIW which includes sensing area are 0.05 and 0.1 for high and low TZs. Comparison table show high sensitivity and small size of the proposed sensor with respect to similar structures.

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