Differential Sensing based on Quasi-Microstrip-Mode to Slot-Mode Conversion

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***Abstract*— In this paper, a differential sensor and comparator based on a mode conversion detector implemented by means of a slotline resonator is proposed for the first time. The sensor divides the input signal between two identical sensing elements, a pair of microstrip lines loaded with complementary split ring resonators (CSRRs). Such CSRRs are symmetrically etched in the ground plane at both sides of the slotline. Therefore, by truncating symmetry, e.g., by loading one of the CSRRs with the reference (REF) sample and the other one with the sample under test (SUT), the slot mode is generated in the slotline resonator. The signal level associated to this mode, which can be inferred by means of a slotline/microstrip transition, depends on the level of asymmetry generated by CSRR loading. Consequently, the proposed structure is useful for differential sensing, where a single input and output port suffices to excite the sensor and to measure the output variable, the magnitude of the transmission coefficient.**

***Index Terms* — Microwave sensor, differential sensor, complementary split ring resonator (CSRR), mode conversion, microstrip line, slotline.**

I. Introduction

PURE DIFFERENTIAL sensors are implemented by means of a pair of identical elements, sensitive to the variable under measurement (measurand) [1]-[5]. One of such elements provides an output signal determined by the reference measurand, whereas the output signal of the other sensing element is given by the measurand under test, and the differential output signal is merely the difference between the individual signals generated by each sensor element. For differential permittivity sensing using microwaves, a pair of transmission lines loaded with identical resonant elements, very sensitive to the properties of the surrounding medium, is typically used [3],[5]. In these sensors, the input variable is the differential permittivity between a reference (REF) sample and a sample under test (SUT), whereas the output variable depends on the specific sensor configuration.

If the pair of sensing lines are independently excited, the difference in the transmission coefficient measured at both lines is typically the considered output variable. In practice, such differential output variable can be obtained by measuring the cross-mode transmission coefficient of the four-port structure (provided the lines are uncoupled) [4],[5]. This mode-conversion approach provides high sensitivity, and has been applied to the measurement of the complex permittivity of liquid samples [4], and to the measurement of electrolyte concentration in extremely diluted solutions [5].

To reduce system complexity, the pair of lines can be arranged in a splitter/combiner configuration [6],[7], resulting in a two-port based differential sensor. In this case, the output variable is the frequency and/or the amplitude difference between the pair of notches that are generated when the resonant elements of the lines are asymmetrically loaded. Similar sensors, i.e., also based on frequency splitting, can be implemented by cascading a pair of identical resonators in a single line [8]. Although these frequency splitting sensors are based on two-port structures, their sensitivity and resolution is limited as compared to mode-conversion sensors.

In this paper we report a two-port differential sensor for dielectric characterization, where mode conversion is the sensing principle. The resolution and sensitivity of these sensors is superior to those of frequency splitting sensors, whilst measuring the differential dielectric constant does not require a four-port measurement.

II. Sensor Principle, Design and Simulation

The layout of the proposed sensor is depicted in Fig. 1. It consists of a pair of identical CSRR-loaded microstrip line segments connected through a T-junction to the input access line. The CSRRs are symmetrically etched with regard to the axial plane of a slotline, implemented in the ground plane of the microstrip line, as shown in Fig. 1. According to this configuration, if the CSRRs are symmetrically loaded, the symmetry plane is a magnetic wall, and the (odd) slot mode cannot be generated. Under these conditions, the injected input power is reflected back to the source and partially radiated, due to the effects of the CSRRs. By contrast, if one of the CSRRs is loaded with a REF sample and the other one with the SUT sample, the difference in the resonance frequencies of both CSRRs causes an asymmetry able to excite the slot mode in the slotline. Since mode conversion depends on the level of asymmetry, the proposed structure is useful for differential sensing. To collect the mode conversion level, a slotline/microstrip transition is added to the structure, as depicted in Fig. 1 [9]. Thus, the output variable in the proposed two-port differential sensing structure is the transmission coefficient between the input and the output port.

The CSRRs have been designed in order to resonate at roughly $f_0 = 1.5$ GHz, when they are loaded with the REF sample (in the first part of this work, the reference sample is a

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slab of *Rogers RO4003C* substrate with dielectric constant ε_r = 3.55, thickness h = 1.5 mm and loss tangent tanδ = 0.0030). The resulting dimensions are indicated in the caption of Fig. 1. The considered substrate of the sensor is the *Rogers RO3010* substrate with dielectric constant ε_r = 10.2, thickness h = 1.27 mm and loss tangent tanδ = 0.0027. The input and output access microstrip lines, as well as the pair of lines between the T-junction and the CSRRs, are 50-Ω lines (with width of 1.12 mm). The microstrip line sections on top of the CSRRs are wider in order to enhance the coupling with the CSRRs. Concerning the slot line (short-circuited at the extremes), its width has been set to 0.4 mm, corresponding to a characteristic impedance of roughly 50 Ω. Concerning the slot length, it corresponds to one wavelength (λ) at f_0, so that the slot resonates at such frequency. The slot-line/microstrip transition has been located at $\lambda/4$ from the right-hand side extreme of the slot, since at this position the electric field in the slot is maximized, and this favors mode conversion between the slot mode and the quasi-microstrip mode [9]. Similarly, the imaginary line connecting the centers of the CSRRs (transverse to the slotline resonator axis) is situated at $\lambda/4$ from the left-hand side extreme of the slotline resonator, provided this is the optimum distance for the generation of the slot mode from an asymmetry in the CSRR pair.

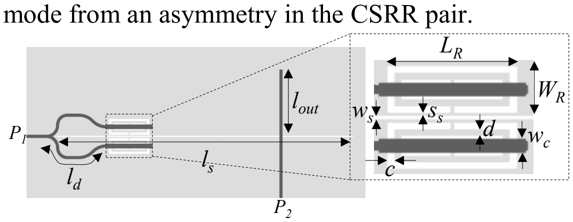

Fig. 1. Topology of the designed sensor. Dimensions are (in mm): L_R = 14.64, W_R = 6.50, $c = d$ = 0.80, w_c = 1.68, $w_s = S_s$ = 0.40, l_{out} = 23.46, l_s = 107.60, l_d = 26.32. The ground plane where the CSRRs and the slotline resonator are etched is depicted in grey color.

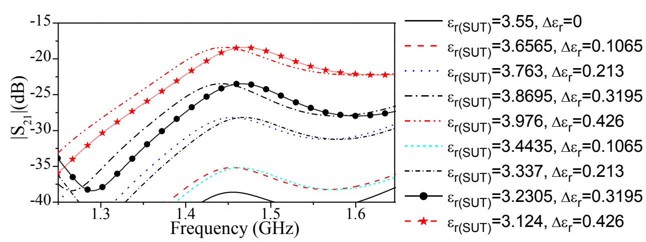

Fig. 2. Transmission coefficient of the structure of Fig. 1 corresponding to several differential loadings of the CSRRs, as indicated in the figure.

To verify the functionality of the proposed structure as differential sensor, we have carried out simulations by considering the above-cited REF material, and a set of hypothetical SUTs obtained from the REF sample by perturbing its dielectric constant, maintaining the loss tangent unaltered. The results, inferred from the *ANSYS HFSS* commercial simulator, are depicted in Fig. 2. It can be seen that the transmission coefficient experiences significant variations when the dielectric constant is perturbed. Note that increasing/decreasing the dielectric constant of the SUT with regard to the REF sample a certain level has the effect of shifting down/up the frequency of maximum transmission, keeping such transmission level unaltered. Thus, it is possible to determine the sign of the differential dielectric constant.

III. Experimental Validation

The photograph of the fabricated sensor is depicted in Fig. 3 (the *LPKF H100* drilling machine has been used for sensor fabrication). The first experimental validation of the sensor concerns its functionality as comparator, able to detect tiny differences (or defects) in a SUT, as compared to a REF sample. For that purpose, we have modified the REF sample by drilling sparse hole arrays across the substrate. The responses of the sensing structure are shown in Fig. 4, where the different SUTs are also depicted. It is remarkable that the device is able to detect the presence of a single hole, and the magnitude of the transmission coefficient severely increases as the density of holes increases. Thus, sensor resolution is good, and sensor sensitivity with the density of holes is high.

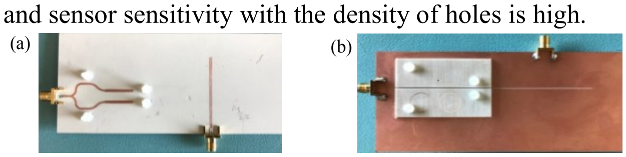

Fig. 3. Photograph of the fabricated sensor. (a) Top view; (b) bottom view with REF and SUT samples attached to the substrate by means of Teflon screws.

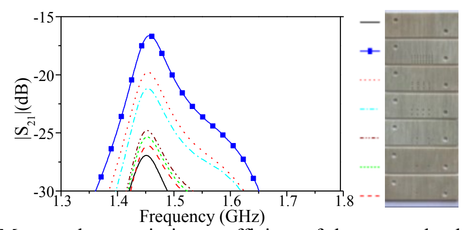

Fig. 4. Measured transmission coefficient of the sensor loaded with different SUT samples consisting of the REF sample with different densities of holes drilled across the substrate.

The sensor is also useful to estimate the dielectric constant of the SUT sample. It has been verified from electromagnetic simulations (not shown) that the dependence of the output variable of the sensor (the maximum value of the transmission coefficient magnitude) with the loss tangent of the SUT is negligible. For that reason, it is possible to infer the dielectric constant of the SUT sample from the measurement of a single output variable. For this purpose, air is the considered REF material, provided any dielectric material exhibits a larger dielectric constant. Fig. 5(a) shows the measured responses of the sensor for different SUT samples (*Arlon*, *FR4* and *RO3010* slabs with dielectric constants 2.43, 4.5 and 1.02 respectively), whereas Fig. 5(b) depicts the measured differential maximum transmission coefficient ($\Delta|S_{21}|_{\max} = |S_{21}|_{max,REF} - |S_{21}|_{max,SUT}$), with the differential dielectric constants ($\Delta\varepsilon_r = \varepsilon_{r,REF} - \varepsilon_{r,SUT}$). From such data points, a calibration curve has been inferred (by means of a curve fitting tool software), and such curve can be used to determine the differential dielectric constant from the measurement of the differential maximum value of the transmission coefficient. To demonstrate the potential of the structure as differential sensor, able to provide the dielectric constant of the SUT sample in real time, we have considered several SUTs samples. Particularly, a piece of *Rogers RO4003C* ($\varepsilon_{r,SUT}$ = 3.55) substrate and two slabs of 3D-printed materials (fabricated by means of the *Ultimaker 3 Ext. model* 3D-printed). Such 3D-printed materials are *PLA* (*Polylactic Acid*) and *MT-COPPER* with nominal dielectric constants of 3 and 7.6 respectively (those values have been obtained using a *Agilent 85072A* resonant cavity). Note that the thickness of the considered samples is roughly the same (1.5 mm), in order to avoid cross sensitivities against thickness effects. The responses with such SUT samples are also depicted in Fig. 5. Considering the maximum transmission coefficient of each sample, the extracted differential dielectric constant for *RO4003C*, *PLA* and *MT-COPPER* are $\Delta\varepsilon_r = 2.42$, $\Delta\varepsilon_r = 2.10$, and $\Delta\varepsilon_r = 6.02$ respectively. With these results, and considering *Air* as the reference sample, the measured dielectric constant of each sample is 3.42, 3.10 and 7.02, respectively (i.e., the sensor accuracy is better than 92.4%).

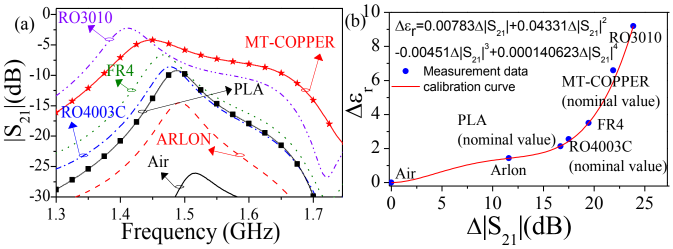

Fig. 5. (a) Measured transmission coefficient of the sensor by considering air as REF material and different SUT samples; (b) dependence of the differential dielectric constant with the differential transmission coefficient and calibration curve.

IV. Discussion And Comparison to other Sensors

Most microwave sensors for dielectric constant measurements are based on frequency variation [10]-[16] or frequency splitting [6]-[8]. Thus, comparing the sensor proposed in this work with those frequency-based sensors is not straightforward. Nevertheless, the reported sensor exhibits excellent resolution, as derived from the fact that minuscule perturbations in material composition are detected (see Fig. 4, where the presence of a single hole in the REF material is perfectly detected). In [4], the reported differential sensor is based on the variation of the cross mode transmission coefficient, and the measured (maximum) sensitivity with the differential dielectric constant is found to be roughly 0.43 dB, i.e., not as good as the one inferred in this paper (8.10 dB). In [4], the effects of the dielectric constant and loss factor of the SUT on the output variables (magnitude and frequency of the maximum cross mode insertion loss) are not decoupled. By contrast, the proposed sensor is insensitive to the loss tangent of the SUT, and, therefore, the dielectric constant can be inferred from a simple single-ended measurement, involving one output variable.

TABLE I
Comparison of various sensors with good accuracy

Ref.	f_0 (GHz)	Accuracy (%)	*Technology*	*Diff. Meas.*
[10]	1.286	96.46 / 97.36	Planar	No
[14]	2.19	95.00 / 98.6 / 99.13/ 99.77	Planar	No
[16]	2.41	99.09 / 97.87 / 98.13	Planar+ *smd*	Yes
T. W.	**1.5**	**96.6 / 95.4 / 92.4**	**Planar**	**Yes**

Table I compares some dielectric constant sensors exhibiting good accuracy. The sensors reported in [10],[14] exhibit comparable accuracy to ours, but they do not operate differentially. The differential sensor of [16] exhibits very good accuracy, but the approach needs *smd* components (i.e., 50 Ω resistors).

V. Conclusions

In conclusion, a differential sensor and comparator based on a quasi-microstrip-mode to slot-mode conversion detector has been reported. The sensitive part of the sensor consists of a pair of CSRR-loaded lines fed by a common port, and placed symmetrically at both sides of a slotline resonator. By differential loading of the CSRRs, symmetry is truncated and the slotline resonator is excited, thereby generating an output signal at the output (microstrip) port of the structure, thanks to the coupling between the slot mode and the quasi-microstrip mode. It has been demonstrated that the structure is useful to detect small differences between samples (comparator functionality), and to measure the dielectric constant of dielectric slabs (samples under test –SUTs).

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