Reflective-Mode Phase-Variation Permittivity Sensors Based on Coupled Resonators

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***Abstract*—This paper presents a novel strategy for the implementation of highly sensitive reflective-mode (one-port) phase-variation permittivity sensors based on coupled resonators (the sensing elements). It is demonstrated that by tuning the frequency of the feeding harmonic signal in the vicinity of the resonance frequency of the isolated resonators, and by weakly coupling the resonant elements, the phase of the reflection coefficient (the output variable) experiences a significant variation with the dielectric constant of the material under test (MUT), resulting in a high sensitivity. Two prototype examples, based on a pair of step-impedance resonators (SIRs), are presented as proof-of-concept demonstrators for validation purposes. The achieved sensitivity in one of the sensors is 468º, providing an unprecedented figure of merit (or ratio between the maximum sensitivity and the area of the sensing region expressed in terms of the squared guided wavelength) of FoM = 27419º/λ^2.**

Keywords*—coupled resonators; dielectric characterization; permittivity sensor; phase-variation sensor; reflective sensor.

I. INTRODUCTION

Sensitivity optimization is one of the most challenging aspects in sensor design. Concerning planar microwave sensors, the subject of this work, the canonical input variable is the permittivity of the so-called material under test (MUT), although such sensors can be applied to the measurement of other physical variables related to it, such as temperature, humidity, material composition, motion variables, etc. Concerning the output variable, it depends on the specific implementation. Thus, there are microwave sensors where the output variable is the resonance frequency of the sensing (resonant) element. Such resonant sensors constitute the most numerous set of microwave sensors, at least in terms of the available literature [1]-[10]. The reason is that frequency-variation sensors combine small size, good accuracy, high sensitivity, and these sensors are able to provide the complex permittivity of the MUT (in this case an additional output variable, typically, the magnitude of the resonance peak or notch, is also necessary). However, frequency-variation sensors need wideband signals for sensing. Specifically, the output dynamic range (related to the input dynamic range and to the sensitivity) determines the required bandwidth. This bandwidth limitation applies also to the so-called frequency-splitting sensors [11]-[20], a type of quasi-differential sensors robust against common-mode stimuli (and therefore immune in front of cross-sensitivities related to ambient factors, such as temperature or humidity).

By contrast, there are microwave sensors that operate at a single frequency, such as the so-called coupling-modulation sensors [21]-[29] and phase-variation sensors [30]-[39]. The latter exhibit the additional advantage of being more robust against the effects of electromagnetic interference and noise. Both transmission-mode [30]-[32] and reflective-mode [33]-[39] phase-variation sensors have been reported. It has been recently demonstrated that very good sensitivities can be achieved by means of step-impedance lines made of quarter-wavelength sections terminated with a sensing resonator (either distributed or semi-lumped) [33],[39].

In the present paper, we report a novel strategy for sensitivity optimization in reflective-mode phase-variation sensors, consisting in the use of coupled resonators as sensing elements. If the resonators are weakly coupled, the phase of the reflection coefficient experiences a significant variation around f_0, the resonance frequency of the uncoupled resonator. Thus, by tuning the frequency of the feeding signal in the vicinity of f_0, a significant sensitivity in the phase of the reflection coefficient, the output variable, with the dielectric constant of the material under test (MUT), the input variable, can be achieved, as it will be demonstrated.

II. THE SENSING CONCEPT

In reflective-mode phase-variation sensors, in order to achieve a high sensitivity, it is necessary that the phase of the reflection coefficient experiences a significant variation with frequency at the operating frequency, when the sensing element (either a distributed or a semi-lumped resonator) is covered with the MUT acting as reference. In a resonant element, the maximum phase variation occurs at resonance, and it increases with the quality factor. For this reason, for sensitivity optimization, an open-ended quarter-wavelength based reflective-mode phase-variation sensor (equivalent to a grounded series resonator) should exhibit a high characteristic impedance, whereas a low impedance is

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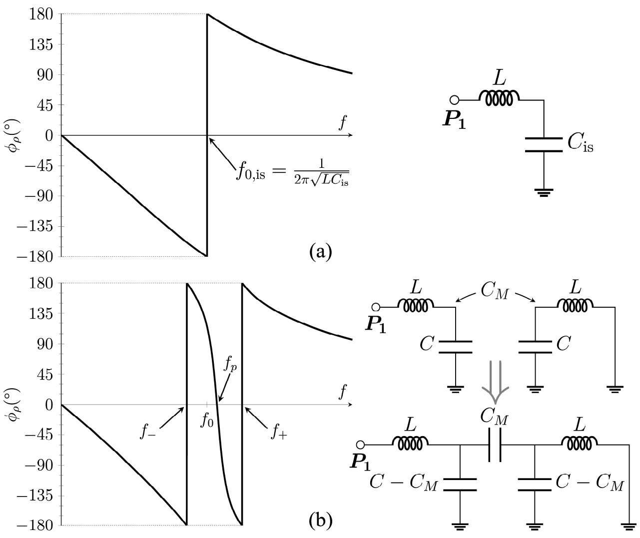


Fig. 1. (a) Isolated series resonator connected to grond and phase of the reflection coefficient; (b) Two (electrically) coupled resonators and phase of the reflection coefficient. C_{is} is the capacitance of the isolated resonator and C is the self-capacitance of the uncoupled resonator (i.e, with the presence of the other resonator short-circuited to ground).

necessary to boost up the sensitivity in sensors implemented by means of open-ended half-wavelength sensing resonators [33]. In [33], it was demonstrated that the sensitivity can be unprecedentedly enhanced by cascading quarter-wavelength high/low impedance line sections (alternating) to the sensing resonators. This does not alter the size of the sensing region (the sensing resonator), but it increases the overall sensor size. In this paper, we propose a new sensing concept useful for sensitivity optimization in reflective-mode phase-variation sensors, based on the use of a sensing resonant element weakly coupled to an identical resonator. By this means, there is a split in the resonance frequencies, and the phase experiences a 360º excursion between these two frequencies. If the resonators are weakly coupled, the two generated resonance frequencies (f_- and f_+, satisfying $f_- < f_0 < f_+$) are very close to each other, and the derivative of the phase with frequency in the vicinity of f_0, the resonance frequency of the uncoupled resonator, can be forced to be very high (Fig. 1 illustrates this concept).

III. Analysis

In the last circuit of Fig. 1(b), the input reactance is

$$\chi_{in} = \frac{(1-k^2)\dfrac{\omega^4}{\omega_0^4} - 2\dfrac{\omega^2}{\omega_0^2} + 1}{C\omega\left\{\dfrac{\omega^2}{\omega_0^2}(1-k^2) - 1\right\}} \tag{1}$$

where ω is the angular frequency, $\omega_0 = 2\pi f_0 = 1/\sqrt{LC}$ is the angular resonance frequency of the uncoupled resonator, and $k = C_M/C$ is the electric coupling coefficient, C_M, C and L being the mutual capacitance, the resonator's capacitance, and the resonator's inductance, respectively. Inspection of (1) reveals that the two zeros in the reactance (given by those frequencies that null the numerator) are

$$\omega_\pm = 2\pi f_\pm = \frac{\omega_0}{\sqrt{1 \mp k}} \tag{2}$$

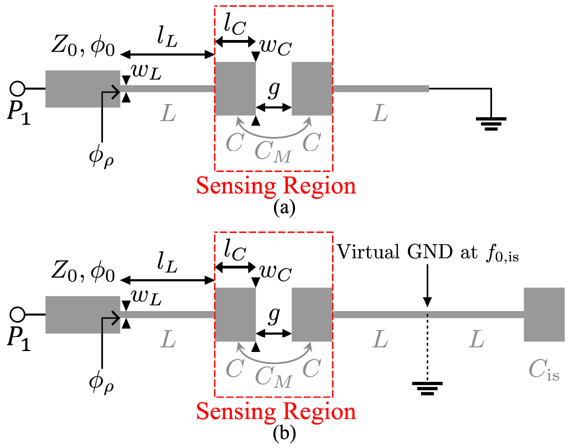


Fig. 2. Typical topology of the proposed reflective-mode phase-variation sensor based on weakly coupled SIRs (a), and equivalent topology that avoids the ground connection (and hence a via) of the right-hand side SIR (b). Relevant dimensions as well as the sensing region are indicated. All SIR elements share the same dimensions. Z_0 = 50 Ω is the reference port impedance.

whereas the pole (i.e., the frequency where the denominator is null) is found to be

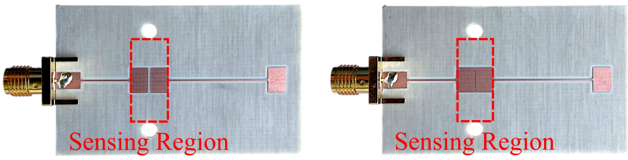
$$\omega_p = 2\pi f_p = \frac{\omega_0}{\sqrt{1-k^2}} \tag{3}$$

Note also that $f_- < f_p < f_+$ in coherence with Fig. 1(b). It is thus clear that if the coupling is weak, then k << 1, and consequently, f_- and f_+ are very close to each other. Under these conditions, the phase of the reflection coefficient between f_- and f_+ experiences a strong variation. Hence, by tuning the operating frequency of the sensor between f_- and f_+, the sensitivity of the phase of the reflection coefficient, ϕ_ρ, with the dielectric constant of the MUT, $\varepsilon_{\mathrm{MUT}}$, is expected to be high.

IV. Sensor Design, Implementation and Results

Let us synthesize the sensor structure of Fig. 1(b) by considering weakly coupled step-impedance resonators (SIRs). The topology is the one depicted in Fig. 2(a), where the elements of the circuit model of Fig. 1(b) are indicated (implementation in microstrip technology is considered in this work). Note that the narrow strips of the SIR correspond to the inductances (L), whereas the wide metallic patches provide the capacitances (C). Since the capacitive patches are edge-coupled, the mutual capacitance, C_M, is intrinsically small, thereby providing weak coupling. Nevertheless, such coupling can be arbitrarily reduced by separating the patches.

According to the topology of Fig. 2(a), the right-hand side SIR (a mirror of the one connected to the 50-Ω access line) should be grounded by the inductive strip. In order to avoid a via connected to ground, the topology of Fig. 2(b) is actually the one considered for sensor implementation. This topology is equivalent to the one of Fig. 2(a) provided the operating frequency is set to $f_{0,\mathrm{is}}$, the resonance frequency of the isolated SIR [see Fig. 1(a)]. Note that at this frequency, the added SIR, with inductance L and capacitance C_{is}, provides a virtual ground at the central plane between the face-to-face SIRs of the right-hand side, exactly at the position of the ground connection in Fig. 2(a).



(a) (b)

Fig. 3. Photograph of the fabricated sensor A (a) and B (b). Dimensions (in mm) are: $w_L = 0.3$, $l_L = 10$, $w_C = 5$, $l_C = 3.65$. The gap separation is $g = 0.5$ mm for sensor A and $g = 0.2$ mm for sensor B. In all the cases, the 50-Ω access lines are 3.33 mm wide and 5 mm long.

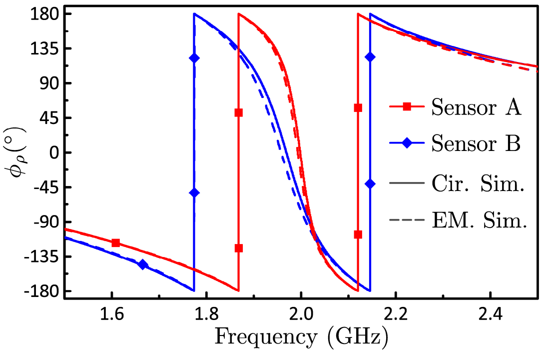


Fig. 4. Phase response of the reflection coefficient for sensors A and B.

We have fabricated two specific sensors, where the difference is the gap separation between the metallic patches (and hence the coupling), see Fig. 3. The considered substrate is the *Rogers RO4003C* with dielectric constant $\varepsilon_r = 3.55$, thickness h = 1.524 mm and loss factor tanδ = 0.0021. Dimensions are given in the caption of Fig. 3. Figure 4 depicts the phase response (reflection coefficient) inferred by electromagnetic simulation (using *Keysight ADS*) by excluding losses and the access lines, as well as the one inferred from circuit simulation. The extracted parameters of the isolated resonator are L = 6.34 nH, and C_{is} = 1.00 pF (providing $f_{0,\text{is}} = 2$ GHz). C and C_M have been extracted from L, f_- and f_+ (providing C = 1.02 pF and C_M = 0.13 pF for sensor A, and C = 1.07 pF and C_M = 0.20 pF for sensor B). As expected, the separation between the frequencies f_- and f_+ is more pronounced in Sensor B, since the coupling is tighter.

According to the presented theory, the sensitivity in Sensor A should be higher, as far as the coupling is weaker in this sensor. To validate this, we have inferred the phase of the reflection coefficient at $f_{0,\text{is}}$ as a function of the dielectric constant of the MUT (considered to be 6 mm height) for both sensors by electromagnetic simulation (using *CST Studio Suite*). The results are depicted in Fig. 5, where the sensitivity $S = d\phi_\rho/d\varepsilon_{\text{MUT}}$ is also included. It can be seen that in the limit of small variations of the dielectric constant of the MUT as compared to that of air, the reference value, the sensitivity is superior in Sensor A, as expected. Specifically, $S = -468°$ in senor A and $S = -140°$ in sensor B.

Experimental validation of the sensors has been carried out by considering uncladded substrates that exhibit dielectric constants of 2.7 (estimated for PLA), 3.55 (for *Rogers RO4003C*), 4.4 (for *FR4*), and 10.2 (for *Rogers RO3010*). Actually, we have stacked several samples in order to satisfy the requirement of 6-mm height MUTs. The

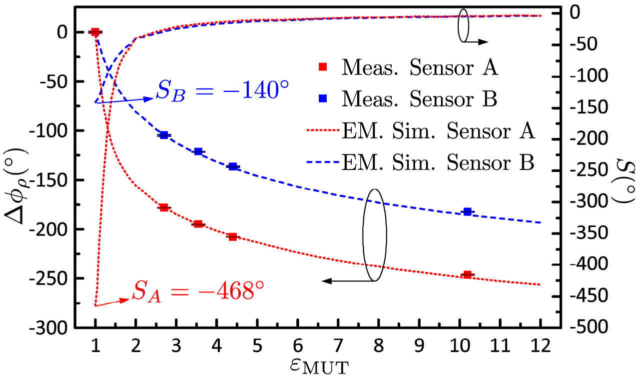


Fig. 5. Differential phase of the reflection coefficient ($\Delta\phi_\rho = \phi_\rho - \phi_{\rho,\text{REF}}$) at $f_{0,\text{is}}$ as a function of the dielectric constant of the MUT, and sensitivity for sensors A and B. $\phi_{\rho,\text{REF}}$ is the phase of the reflection coefficient when $\varepsilon_{\text{MUT}} = 1$ (corresponding to air, the considered reference MUT).

measured phases of the reflection coefficient for the different considered samples are indicated in Fig. 5 (the error bars, corresponding to the standard deviation of three independent measurements, are included in the figure), where it can be appreciated a good agreement with the simulations. Obviously, the sensitivity of the sensors has been optimized for $\varepsilon_{\text{MUT}} = \varepsilon_{\text{air}} = 1$, since the designed isolated SIRs resonate at $f_{0,\text{is}}$ when the load is air. Nevertheless, sensitivity optimization in the vicinity of different values of the reference ε_{MUT} can be considered.

V. Competitive Advantages of the Proposed Sensor

The main relevant advantage of the proposed sensors is the fact that the maximum sensitivity can be enhanced at wish by merely reducing the coupling between the resonant elements (SIRs in our case). By contrast, in the reflective-mode phase-variation sensors reported in [33]-[35],[39], sensitivity enhancement requires cascading high/low impedance quarter-wavelength transmission line sections, thereby representing a penalty in terms of overall sensor size. Moreover, the reported sensors are based on semi-lumped, i.e., electrically small, planar resonators. The total sensor size, excluding the access lines, is only $0.461\lambda \times 0.223\lambda$ and $0.458\lambda \times 0.223\lambda$ for sensor A and B, respectively, λ being the guide wavelength at $f_{0,\text{is}}$. In addition, the area of the sensing region is $A_s = 0.082\lambda \times 0.209\lambda$ and $A_s = 0.078\lambda \times 0.209\lambda$ for sensor A and B, respectively. With these values, the figure of merit is FoM = $S_{max}/A_s = 27419°/\lambda^2$ for sensor A, and FoM = $8531°/\lambda^2$ for sensor B, i.e., very competitive (indeed, an unprecedented FoM for sensor A).

VI. Conclusion

In conclusion, a novel sensing strategy for one-port reflective-mode phase-variation sensors has been presented in this paper. It has been demonstrated that by weakly coupling a pair of resonators, one of them connected to the access line, the excursion experienced by the phase of the reflection coefficient between the (split) resonance frequencies is very high, and this favors sensitivity optimization. Validation has been demonstrated by means of a pair of sensors exhibiting different coupling level between the considered resonators (SIRs).

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