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New approach for dielectric constant detection using a microstrip sensor

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ABSTRACT

A novel dielectric constant detection method using a microstrip sensor is presented in this paper. The aim was to estimate the dielectric constant in the space above a resonator which was the basic part of the sensor. Variation in resonant frequency of the resonator was considered as the criterion for detection of the dielectric constant variation. The microstrip resonator was designed using coupled stepped impedance open stubs. The circuit model of the resonator was then extracted and the resonant frequency as a function of the dielectric constant was obtained. Applicability of the proposed method was verified in experimental studies.

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1. Introduction

Investigation of dielectric constant of various materials has been performed in many cases as an index of their physical and chemical changes. Among the existing applications of this approach, design of gas sensors, humidity detection, and also detection of type and quality of vegetable oil using dielectric constant [1–5] are notable. There are various methods for measurement of dielectric constant of materials and its changes including [6–8]. Despite the achievements so far in terms of both applications and measurement methods of dielectric constant, there seems to be a huge potential for further developments. One area where limited contribution has been made is designing microwave sensors. Due to the advantages of microwave devices and possibility of their utilization in wireless systems, they have been vastly considered for building diverse sensors. Among many industrial applications of microwave sensors [9,10], an example is a microwave level sensor for molten glass able to operate in an industrial furnace which was proposed and tested in [9] while in another application [10] a new microwave sensor for the detection of cracks in metallic materials was presented. Materials in forms of gas, liquid and solid have been investigated using microwave sensors [5,11–13] which indicates to their vast applicability. Microstrip resonators are common components in design of microwave sensors which provide small size and low fabrication cost. Moreover, these resonators are capable of being connected to other parts of a wireless monitoring system. Split-ring resonator, parallel ring resonators, quarter and half wavelength resonators and interdigital coupled lines have been used for developing microwave resonators in [3,4,10–14]. A change in property of the substrate of the resonator as a result of proximity to different materials has been investigated in a number of microstrip sensors [2]. This is while in some other cases, the substrate properties do not change and circumstances governing the resonator vary instead [11,12].

In this work, the aim is to develop a new method for detection of dielectric constant of materials using a microstrip-based microwave sensor. A change in the resonant frequency of the microstrip sensor resulting from a change in its effective dielectric constant is considered as the index for defining the dielectric constant of the sample material. In order to illustrate the method, a coupled stepped impedance resonator that was developed and used as the sensor and its circuit model was extracted. Using this model the relationship between the dielectric constant of the tested materials and the resonant frequency of the sensor was obtained. Simple structure, well known governing equations and flexibility in design are the advantages of the proposed resonator against the common resonator such as split-ring resonator and parallel ring resonators. The method was successfully examined in experiments using the sensor. In the following sections, the sensor, extraction of its model and governing equations are presented first receded by results of the experiments and their discussions.

2. Microstrip sensor structure, modeling and analysis

Variation of the resonant frequency of a resonator based on the environmental changes is the basic concept behind the proposed

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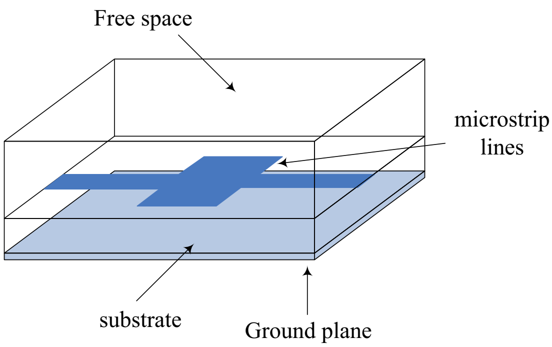

Fig. 1. Typical layout of a microstrip resonator.

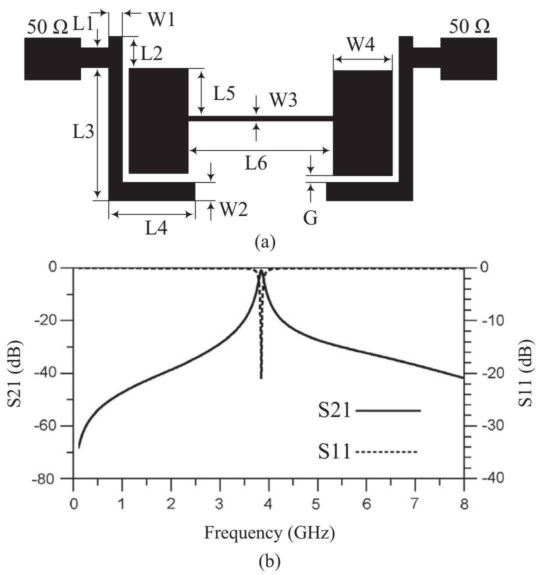

Fig. 2. Proposed resonator (a) layout (b) simulation results.

detection method and sensor design. As it is shown in Fig. 1 a microstrip resonator is composed of four layers: lowest layer is the ground plane, the next layer is high frequency substrate, the next one is strip lines and the top layer is free space.

If in this structure the top layer (with $\varepsilon_r = 1$) is replaced with other materials (with $\varepsilon_r > 1$), the effective dielectric constant of the resonator increases and leads to decreased resonant frequency. This means that the resonant frequency of the resonator is related to the effective dielectric constant which is in turn related to the dielectric constant of the top layer.

Fig. 2 shows the layout and simulation results of the proposed resonator which was used to design the microstrip sensor. The resonator which had arbitrary but typical characteristics was designed on RO4003 substrate with relative dielectric constant of 3.38 and thickness of 20 mil and its dimensions were as follows:

$L_1 = 0.6$ mm, $L_2 = 1$ mm, $L_3 = 4.4$ mm, $L_4 = 2.9$ mm, $L_5 = 1.7$ mm, $L_6 = 7.4$ mm, $W_1 = 0.5$ mm, $W_2 = 0.6$ mm, $W_3 = 0.2$ mm, $W_4 = 2.0$ mm, $G = 0.2$ mm.

As it is shown in Fig. 2a, the proposed resonator was composed of two pair of coupled open stubs that were connected through a high impedance line. Fig. 2b depicts the simulation results of the resonator while the top layer was free space. The resonant frequency was 3.85 GHz with insertion loss/return loss of 0.85 dB/21 dB. Once the relationship between the resonant frequency and the effective dielectric constant of the resonator is obtained, then the sensor criteria to measure this physical quantity would be achieved.

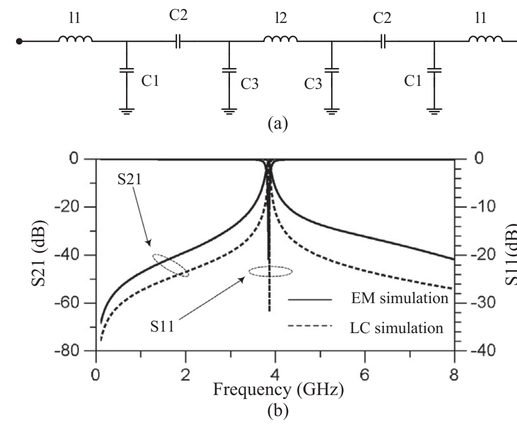

Fig. 3. (a) Proposed circuit model (b) simulation results.

Fig. 3a and 3b shows the proposed circuit model of the resonator and its simulation results respectively. In this model l_1 introduces the inductance of the lines which are connected to the input/output ports, c_1, c_3 represent the bent and rectangular open-ended stubs, and c_2, l_2 introduce the coupling capacitance and inductance of the central line. Using Eqs. (1)–(3) and resonator dimensions, the LC parameters can be estimated as follows:

$l_1 = 0.42$ nH, $l_2 = 4.46$ nH, $c_1 = 0.5$ pF, $c_2 = 0.065$ pF, $c_3 = 0.7$ pF

$$C = \frac{l}{z_c\, v_p} \quad L = \frac{l\, z_c}{v_p} \quad v_p = \frac{c}{\sqrt{\varepsilon_{re}}} \tag{1}$$

For $w/h \leqslant 1$

$$\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left\{\left[1 + 12\frac{h}{w}\right]^{-0.5} + 0.04\left[1 - \frac{w}{h}\right]^2\right\}$$

$$z_c = \frac{\eta}{2\pi\sqrt{\varepsilon_{re}}} \ln\left[8\frac{h}{w} + 0.25\frac{w}{h}\right] \tag{2}$$

For $w/h \geqslant 1$

$$\varepsilon_{re} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2}\left[1 + 12\frac{h}{w}\right]^{-0.5}$$

$$z_c = \frac{\eta}{\sqrt{\varepsilon_{re}}}\left\{\frac{w}{h} + 1.393 + 0.677\ln\left[\frac{w}{h} + 1.444\right]\right\}^{-1} \tag{3}$$

In these equations, C and L are capacitance and inductance of the resonator parts, z_c is the characteristics impedance, v_p represents the phase velocity, w, l and h are the line widths, line lengths and substrate thickness respectively. ε_{re} is the effective permittivity, η is a constant equal to 120π Ω and c represents the light speed.

As it is depicted in Fig. 3b agreement between circuit and EM simulation results of the resonator, confirmed the validity of the proposed model. In order to calculate the relationship between the resonant frequency and LC parameters of the circuit model, firstly the Z parameters of the model were extracted and then the S-parameters were obtained. In (4) Z_{21} is the open-circuit transfer impedance of the circuit model, V_2 is the voltage of the output port, and I_1, I_2 are Input currents to the I/O ports.

$$Z_{21} = Z_{12} = \left.\frac{V_2}{I_1}\right|_{I_2=0} \quad Z_{11} = Z_{22} = \left.\frac{V_1}{I_1}\right|_{I_2=0} \tag{4}$$

Using (4) and the circuit model, Z_{21} and Z_{11} as a function of l_1, l_2, c_1, c_2, c_3 and f (frequency at Hz) were formulated as (5), (6).

$$\begin{aligned}|Z_{21}| = |Z_{12}| &= 0.25\ c_2^2/\pi f \\ &\times \left(-c_3c_2^2 - 2c_1c_2c_3 - c_1c_2^2 + 2l_2\pi^2f^2c_2^2c_3^2 + 4c_2l_2\pi^2f^2c_3^2c_1\right. \\ &+ 4c_3l_2\pi^2f^2c_2^2c_1 - c_3c_1^2 - c_2c_1^2 + 2l_2\pi^2f^2c_1^2c_3^2 + 4l_2\pi^2f^2c_1^2c_2c_3 \\ &\left.+ 2l_2\pi^2f^2c_1^2c_2^2\right)\end{aligned} \tag{5}$$

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