An SIW Resonator Sensor for Liquid Permittivity Measurements at C Band

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***Abstract*—This letter presents a novel substrate integrated waveguide (SIW) resonator sensor that is specifically designed to measure the complex permittivity of liquids. The resonant characteristics of the sensor are influenced by liquids through a slot opened on the top plane. The inverse problem of obtaining permittivity is solved with artificial neural network. Experiments were performed with an SIW resonator sensor designed at C band. Experimental data were reported and they agreed well to the reference values. The sensor is simple and low cost, which may be applied to permittivity measurements in applications at the industrial, scientific and medical (ISM) frequencies.**

***Index Terms*—Artificial neural network (ANN), complex permittivity, microwave industrial application, resonator, substrate integrated waveguide (SIW).**

I. Introduction

COMPLEX permittivity measurement is one of the research issues of the scientific community [1]. The complex permittivity measurement technology has experienced decades of development, and has produced a variety of measuring methods. Over the years, a number of planar circuits, such as microstrip lines, coplanar waveguides, and strip lines have been reported to measure the complex permittivity of materials at microwave frequency successfully [2], [3]. Recently, researches have been carried out on the microstrip resonator sensor which measures the complex permittivity of liquids with medium/high loss, such as binary liquid mixtures of methanol and ethanol [4]. In this letter, a novel substrate integrated waveguide (SIW) resonator with a slot on the top plane is proposed. An SIW provides the features of traditional rectangular waveguide in planar form and therefore, is a low-profile alternative for rectangular waveguide [5]. Compared with the microstrip resonator sensor presented in [4], an SIW resonator sensor needs no extra metal shield to protect the inner resonant structure from direct liquid contact. Also, a measurement over a broad permittivity range with high accuracy is possible due to the high quality factor of the SIW resonator sensor [6], [7].

When an SIW resonator sensor is immersed in a liquid under test, the resonant characteristics of the sensor are influenced through the slot opened on the top plane. The resonant characteristics, the resonant frequency, and the quality factor, are extracted from the S-parameters measured by a vector network analyzer (VNA). Then the resonant frequency and quality factor are applied to reconstruct the complex permittivity through an artificial neural network trained by simulated data. The results show that the SIW resonator sensor is suitable for application to complex permittivity measurement with high accuracy and broad permittivity range.

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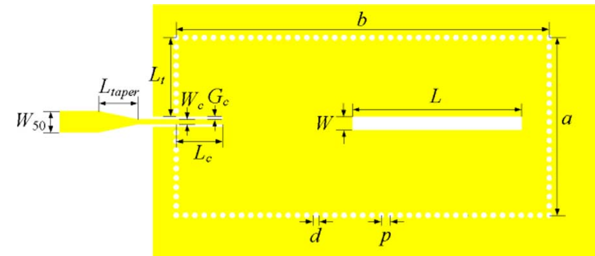


Fig. 1. Structure of the SIW resonator sensor model.

II. Design of the SIW Resonator Sensor

Fig. 1 shows the proposed SIW resonator sensor working at 5.85 GHz (an ISM frequency). The resonant mode of the SIW resonator is TE_{102}. The substrate is F4B-2 with $\varepsilon_r = 2.5$ and $\tan\delta = 0.001$, and the thickness is 1 mm. The dimensions of the resonator are $W_{50} = 2.7$ mm, $L_{taper} = 5$ mm, $W_c = 0.6$ mm, $G_c = 0.4$ mm, $L_c = 6$ mm, $L_t = 10.1$ mm, $a = 22.8$ mm, and $b = 48$ mm. A narrow slot with a length $L = 20$ mm and width $W = 1.6$ mm is opened on the top plane. The dimension of the SIW resonator sensor is 75 mm × 33 mm × 1 mm.

The feed network consists of a 50 Ω microstrip line connected to an SMA adapter, a microstrip taper, and a grounded coplanar waveguide (GCPW). The 50 Ω microstrip line is transformed to the center conductor of GCPW through the taper which minimizes reflection. The gap between the center conductor and grounded plane of GCPW, G_c, is minimized to suppress the undesired power leakage or coupling to other modes. The length of the center conductor, L_c, decides the maximum power transfer from GCPW to SIW [8]. This compact coupling structure is designed for stronger resonance. Fig. 2 shows the measured data of the SIW resonator compared with the simulated data. The detailed comparison of the resonant characteristics between measurement and simulation is listed in Table I. The quality factor of the proposed SIW resonator reaches 334.6, and a good agreement between measured and simulated data is observed.

Due to the structural characteristics of the SIW, the SIW resonator sensor needs no extra metal shield when immersed in the liquids. During measurement, the slot opened on the top plane is completely immersed in the liquids under test, while the coupling structure is kept away from the liquids. The resonant frequency and unloaded quality of the SIW resonator vary

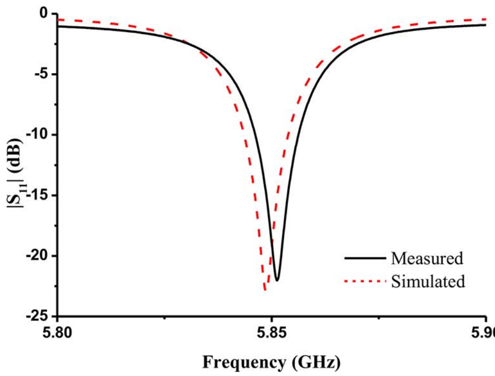
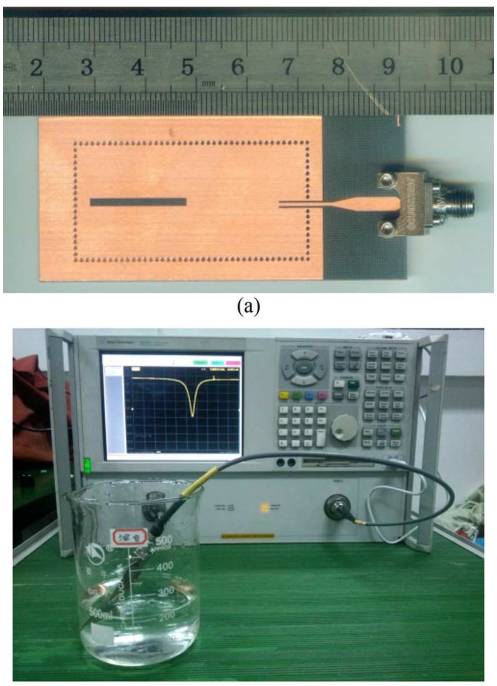


Fig. 2. Measured and simulated reflection coefficients of the SIW resonator.



(a)

(b)

Fig. 3. The SIW resonator sensor and the measurement system. (a) The fabricated SIW resonator sensor, (b) The measurement system.

TABLE I
MEASURED AND SIMULATED RESONANT CHARACTERISTICS

	f_0 (MHz)	Q_0	Q_L	k
Measured	5851.3	334.6	191.2	0.75
Simulated	5848.7	346.2	186.1	0.86

with liquid permittivity. The fabricated SIW resonator sensor and permittivity measurement system are shown in Fig. 3.

III. RECONSTRUCTION METHOD OF THE COMPLEX PERMITTIVITY

The SIW resonator resonant frequency, f, is calculated as

$$f(\mathrm{TE}_{m0q}) = \frac{c_0}{2\sqrt{\varepsilon_r}}\sqrt{\left(\frac{m}{a_{equ}}\right)^2 + \left(\frac{q}{l_{equ}}\right)^2} \tag{1}$$

where a_{equ} and l_{equ} are the equivalent width and length of the SIW resonator, respectively

$$a_{equ} = a - \frac{d^2}{0.95p}, \quad l_{equ} = l - \frac{d^2}{0.95p}. \tag{2}$$

The unloaded quality factor of the SIW resonator is

$$Q_u = \left(\frac{1}{Q_c} + \frac{1}{Q_d}\right)^{-1} \tag{3}$$

where Q_c represents the quality factor of the resonator with lossy conducting walls but lossless dielectric, which is mainly determined by surface resistivity and resonator dimension. Q_d represents the quality factor of the resonator with a lossy dielectric filling but perfectly conducting walls computed by

$$Q_d = \frac{\varepsilon'}{\varepsilon''} = \frac{1}{\tan\delta}. \tag{4}$$

For the designed SIW resonator sensor, the complex permittivity involved in the above equations is effective complex permittivity determined by the complex permittivity of the substrate and liquid under test together. However, the complexity of the relationship between the effective complex permittivity and the complex permittivity of the substrate and liquid impedes the derivation of an analytical solution. The effective solution of the inverse problem, the reconstruction of the complex permittivity according to the measured resonant frequency and unloaded quality factor, is based on back-propagation artificial neural network (BP-ANN). An artificial neural network is an interconnected group of artificial neurons which is based on a mathematical model for information processing. The main idea of BP-ANN algorithm is to divide the learning procedure into forward propagation and reverse revision process. In the process of forward propagation, data are passed from input layer to the hidden layer, and passed though the connection strength of the neural unit (weights) and the transfer rules (excitation function) from hidden layer to the output layer. Once the output of the neural network is consistent with the expected output, the learning procedure will turn into the reverse revision process. A group of data is applied to train the artificial neural network before reconstruction. These data are the mapping relationship from the real and imaginary part of the complex permittivity to the resonant frequency and quantity factor, which are obtained from the simulation results with CST Microwave Studio.

When the training errors are below the given values, the training will stop. At this time, the weight matrix of the artificial neural network is on a suitable state reflecting the rules of the equations mentioned above and the relationship between complex permittivity. When the measured data, the resonant frequency, and the unloaded quality factor of the SIW resonator sensor obtained from measured S-parameters, are placed into the artificial neural network, the real and imaginary part of the complex permittivity will be computed.

IV. MEASUREMENTS AND RESULTS

For measurement over a broad permittivity range, the binary liquid mixtures of ethanol and water are chosen. The SIW resonator sensor was immersed in the liquids under test filled into a 500 mL glass beaker at 20°C. The S_{11} parameters of the SIW resonator sensor immersed in the binary liquid mixtures with different volume fractions were measured from 5.75 to 5.95 GHz by Agilent N5230A VNA. During measurements, the average function of VNA is aimed for reducing random errors. Then the resonant frequency and the unloaded quality factor are extracted from measured S-parameters.

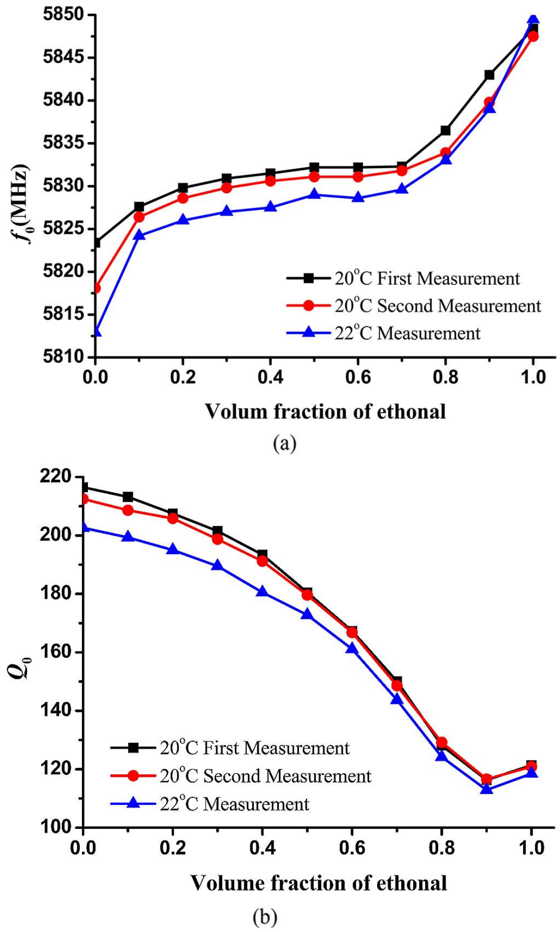


Fig. 4. Measured results with respect to volume fraction of ethanol from 0% to 100%. (a) Resonant frequencies, (b) Quality factors.

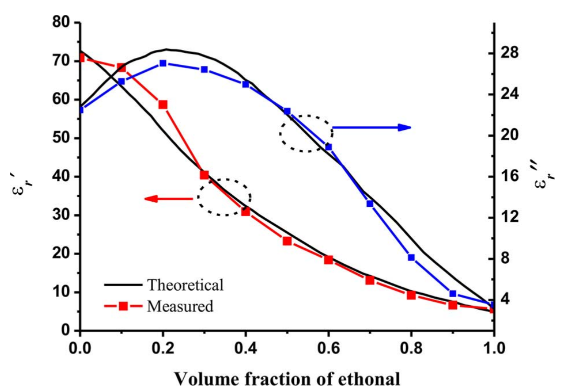


Fig. 5. Reconstructed complex permittivity (real and imaginary parts) with respect to the volume fraction of ethanol from 0% to 100%.

Considering that the random errors when measuring the volume of liquid and the temperature variation will affect the complex permittivity, we analyzed the uncertainty of the complex permittivity measurement. The extracted resonant frequency and unloaded quality from measured S_{11} parameters under different conditions are shown in Fig. 4. An effective method for reducing random errors of measuring volume is multiple measuring (3–4 times) for average values. Maintaining a constant temperature is also important for accurate measurement.

Fig. 5 shows the real and the imaginary parts of the reconstructed complex permittivity. They agree with the values calculated according to the dielectric relaxation parameters of ethanol-water mixture with different volume fractions in [9], [10]. The average relative errors of ε' and ε'' are 5% and 7%, respectively. The proposed SIW resonator sensor is sensitive to the complex permittivity variation of the liquid under test. It can figure out the valley of the unloaded quality factor curve obviously when the volume fraction of ethanol is between 0.8 and 1. However, the inaccuracy of the simulated data will cause higher relative errors when reconstructing the complex permittivity, especially that the condition cannot be simulated accurately when ethanol begins to be added into pure water. An effective solution is to use the SIW resonator sensor to measure different kinds of liquids whose complex permittivity are known, and then use these measured data to train artificial neural network instead of the simulated data. Thus, more accurate reconstructed results will be obtained due to the exclusion of the simulated errors.

V. Conclusion

In this letter, a novel SIW resonator sensor with high-unloaded quality factor has been designed for fast and reasonably accurate complex permittivity measurements. It is not suitable for measurements at lower frequency band due to its dimensions. The sensitivity of the proposed SIW resonator sensor is tested on binary mixtures of ethanol and water with different volume fractions. The artificial neural network for solving inverse problems is applied. The relative errors of ε' and ε'' are 5% and 7%, respectively. The proposed SIW resonator sensor is simple and low cost for permittivity measurements in microwave industrial applications.

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