**FACTA UNIVERSITATIS**
Series: **Electronics and Energetics** Vol. 33, N° 1, March 2020, pp. 61-71
https://doi.org/10.2298/FUEE2001061N

# PARALLEL-STRIP LINE STUB RESONATOR FOR PERMITTIVITY CHARACTERIZATION

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**Abstract**. *A new type of a microwave permittivity sensor with a short open stub as a resonator is introduced. The open stub is realized as a double-sided parallel-strip line without a substrate and can be totally immersed into the measured material. It provides high sensitivity of the resonant frequency nearly proportional to the ratio of square roots of dielectric constants of the measured materials. The sensor is tested in two different frequency ranges and for two different dielectric constant ranges (oils and ethanol-water mixture). Its technology is without any additional technological processes such as vias, air-bridges or defected ground structures. Presented sensor is designed, fabricated and tested showing good agreement between simulations and measurements***.**

**Key words**: *Microwave sensor, microstrip, double-sided parallel-strip line, permittivity measurement.*

## 1. INTRODUCTION

Microwave sensors are being increasingly used as sensing components in many applications [1]. They are sensitive, able to survive overdrives and their signal can be directly transmitted over a distance [2]. One type of microwave sensor is a resonant sensor. Great advantage of this type of sensor is its principle of operation that is based on the resonance frequency and is generally immune to the environmental noise. Besides, the use of the planar technology enables an easy, fast and inexpensive fabrication. Advantages of the planar microwave fabrication process finds wide application in planar structures such as microstrip, CPW and strip line [1,3]. Accordingly, a microwave microstrip resonator is a good choice for a sensor [4-9].

The location of the Material Under Test (MUT) is usually above the microstrip line [4,9], under the pattern etched in the microstrip ground plane [5,6] or above the coupling area of the coupled microstrip structures [7,8]. However, there is one main problem - the

Received March 4, 2019; received in revised form August 21, 2019
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fact that the sensitivity depends on the extent of the field penetration inside the MUT [3]. In all three mentioned positions of the MUT only a part of the field lines is inside the MUT because the field lines in microstrip are predominantly concentrated within the substrate, as presented in Fig. 1.

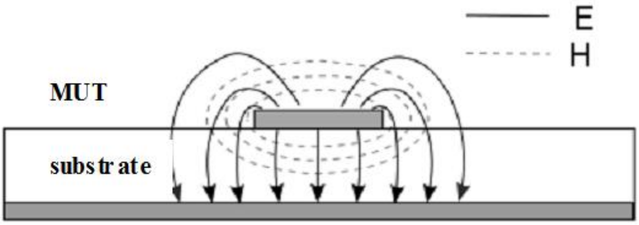



**Fig. 1** Electric (*E*) and magnetic (*H*) field lines in microstrip are stronger within the substrate. Material under test (MUT) is usually above the substrate in the lower field region. Gray areas represent metallization

It is obvious that locating the MUT inside the substrate results in a higher sensitivity [3]. Still, one can insert the MUT (i.e. fluid) through the substrate [10, 11]. This solution is inconvenient especially in cases where thin substrates are used and is suitable only for microfluids. Another solution can be double-sided parallel-strip line printed on dielectric pipes for fluids testing, [12], though it is appropriate for pipes but not for immersing a stub into a fluid. Also, the resonance occurs at low frequencies and open stubs are in this case too long (around 25 cm). Some analogy with a coaxial open stub is given in [4]. Its resonance is also at low frequencies thus an open stub is too long (around 33 cm), and is not practical for a number of applications. Besides, it is tested only for high dielectric constants. The microstrip sensor for immersing into a fluid is presented in [5]. It has disadvantages in the construction and the protection problems during measurements. One solution to problems from [5] is in use of Substrate Integrated Waveguide (SIW) technology [13]. However, the disadvantage of the solution presented in [13] is great number of vias in the SIW technology.

In this paper a new type of a modified microstrip $\lambda/4$ - open stub resonant sensor is introduced. It is suitable for immersing into a fluid and has a short open stub (< 20 mm). The whole structure is in the form of a double-sided parallel-strip line [14,15], i.e. a T-junction with an open stub without a substrate as a sensing part, Fig. 2. The pair of two symmetrical metal strips without a substrate represents the sensing part of the stub. Double-sided parallel-strip line technology is chosen in order to obtain such sensing structure. The absence of a substrate enables each stub strip to be totally surrounded by the MUT. According to this, the total field around the stub strips is inside the MUT and naturally produces higher sensitivity. The sensing stub can be simply immersed into the MUT without any additional preparation or use of any auxiliary structure like cavity. The sharp stopband always exists and the resonant frequency can be clearly measured.

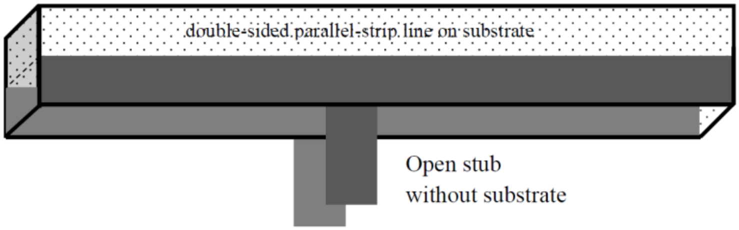



**Fig. 2** Basic layout of a double-sided parallel-strip line T-junction with an open stub without substrate

An open stub is a well-known resonator. The first resonant frequency of an open shunt stub is for the wavelength:

$$\frac{\lambda_{gr}}{4} = \frac{\lambda_0}{4\sqrt{\varepsilon_{reff}}} = L \ , \ \ f_R = \frac{c}{4L}\frac{1}{\sqrt{\varepsilon_{reff}}} \ , \ \ \varepsilon_{reff} = \left(\frac{c}{4L}\right)^2 \frac{1}{f_R{}^2} \tag{1}$$

where $\lambda_{gr}$ is the guided resonant wavelength, $\lambda_0$ is the free space wavelength, $\varepsilon_{reff}$ is the effective dielectric constant and $L$ is the length of the open stub, $f_R$ is the resonant frequency and c is the speed of light. In the microstrip structure $\varepsilon_{reff}$ mainly depends on the dielectric constant $\varepsilon_r$ of the microstrip dielectric substrate because the field lines of the microstrip are predominantly concentrated within the substrate, as presented in Fig. 1. The goal of the paper is to use an open stub without a substrate in which case the material under test totally fills both the area surrounding the substrate and the area commonly occupied by the substrate. In that case $\varepsilon_{reff} \cong \varepsilon_{rMUT}$ induces high sensitivity. The ideal sensitivity, as the shift of the open stub resonant frequency, is equal to the ratio of square roots of dielectric constants of the measured materials, eq. (1).

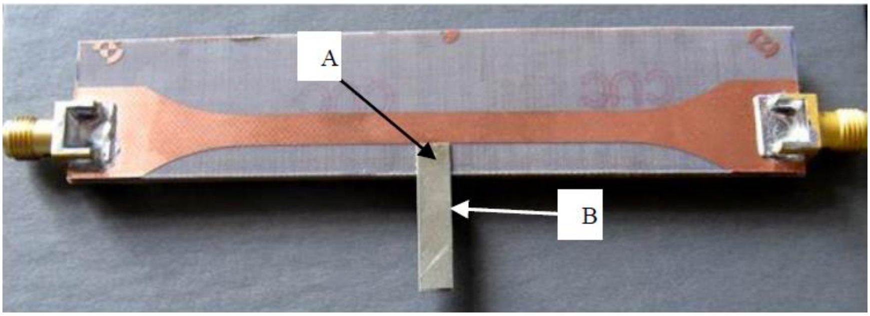
The proposed sensor is fabricated in microstrip printed planar technology without any additional technological process such as vias, air-bridges, defected ground structures (DGS) or many vias for substrate integrated waveguide (SIW). The realization of the sensor was carried out in an easy way using standard photolithographic procedure. Besides, the sensor dimensions are within technological tolerances.

## 2. DESIGN AND FABRICATION

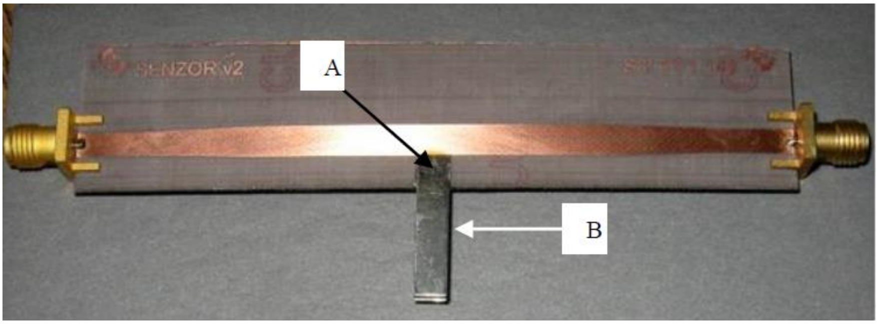
As mentioned previously, the structure is designed in printed planar technology as a double-sided parallel-strip line T-junction. The objective of the design was to fabricate the T-junction with an open stub without a substrate. According to fabrication possibilities, the realized structure is somewhat different from the basic ideal model shown in Fig. 2. The photos of the both sides of the fabricated structure are displayed in Fig. 3.

The main part of the proposed structure is realized on CuClad 217 substrate (with relative dielectric constant $\varepsilon_r = 2.17$ and thickness $h = 1.143$ mm) as a double-sided parallel-strip line T-junction. Layouts of the bottom and the top parts of the structure are presented in Fig.4 and are denoted by gray and black color, respectively. The structure consists of a 4.5 mm wide 50 Ω-double-sided parallel-strip line with a double-sided parallel-strip line open stub in the middle which is 4.75 mm long and 4.5 mm wide as shown in Fig.4. The part of the stub printed on the dielectric substrate serves for bonding the rigid metal strips (A in Fig.3) on both sides while the distance between the strips is the same as the thickness of the substrate (1.143 mm). Since the structure is designed as a symmetrical (balanced) microstrip line, there has to be a transition (BAL-UN) to unsymmetrical (conventional) 50 Ω-microstrip line at its both ports, [15]. In our case, for the used dielectric substrate, the width of this 50 Ω-line is 3.5 mm. Width of the ground plane area at the SMA connector location is 14 mm.

Rigid metal strips, 20 mm long, 4.5 mm wide and 0.3 mm thick, are bonded (conventional eutectic alloy) to the 4.75 mm long stubs (A in Fig.3) on the both sides of the substrate. Free parts of the rigid metal strips are forming 15.25 mm long part of the open stub without a substrate (B in Fig.3).




a) Bottom side of the proposed microwave sensor




b) Top side of the proposed microwave sensor

**Fig. 3** Photograph of the proposed microwave sensor with SMA connectors. A – Part of the metal strip on the substrate; B - Part of the metal strip without the substrate

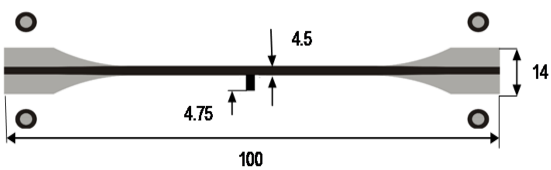
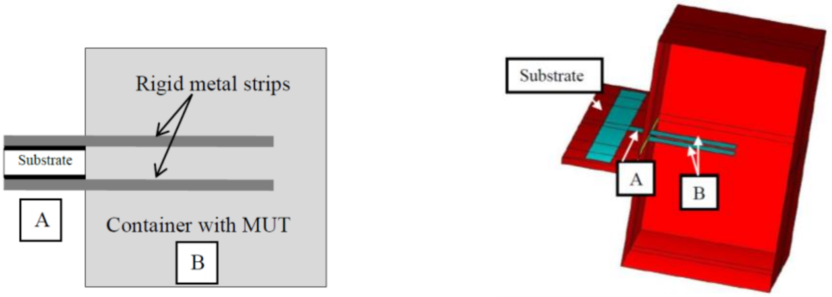



**Fig. 4** Layout of the bottom (gray) and the top (black) side metallization of the proposed double-sided parallel-strip line T-junction with a BAL-UN transition to the conventional microstrip line at both ports

## 3. SIMULATION

The main problem is a double segmented open stub. The shorter part of this stub (part A in Fig. 5) is printed on the substrate and cannot be immersed in the MUT. It is treated like a common double-sided parallel-strip line on a substrate. The part B (Fig. 5) is immersed into the MUT so to be totally surrounded by it.

Simulations were carried out using 3D WIPL-D Microwave Pro program package [16].




a) Segments of the open stub b) WIPL-D Pro simulation model

**Fig. 5** Sketch of the open stub resonator and its WIPL-D simulation model. A - Segment of the stub printed on the substrate (4.75 mm); B - Segment of the stub without the substrate immersed in the MUT (15.25 mm)

The WIPL-D simulation model is presented in Fig. 5b. Simulation results are obtained for two specific ranges of the relative dielectric constants. The first is for $\varepsilon_r$ which ranges from 1.5 to 3, specific for oils, while the second is for $\varepsilon_r$ that ranges from 20 to 80, specific for the water-ethanol mixtures. For the mixture water-ethanol the parameters are taken from [17]. High imaginary parts of $\varepsilon_r$ are incorporated from [17] to calculate real resonant frequency for the measured frequency range (ethanol 70%: 39.5 - i7 and ethanol 96%: 22 - i11). Relative dielectric constant $\varepsilon_{r\text{-}MUT}$ related to the resonant open stub frequencies are presented in diagrams in Fig. 6., Fig. 7. and Fig. 11. For the reference air ($\varepsilon_r$ = 1) simulated resonant frequency is 3.74 GHz.

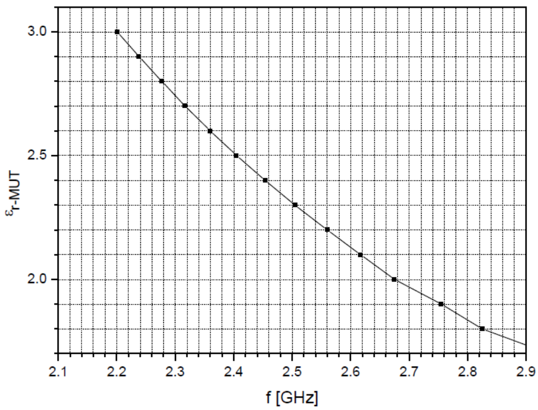



**Fig. 6** Simulated diagrams for the first specific range of the MUT relative dielectric constants (1.5–3.0) vs. the resonant frequencies

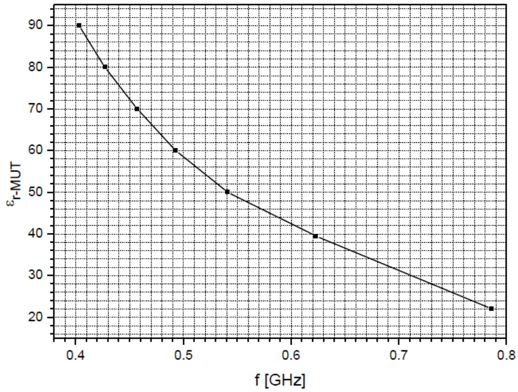



**Fig. 7** Simulated diagrams for the second specific range of the MUT relative dielectric constants (20–80) vs. the resonant frequencies

## 4. MEASUREMENT

The measurements are performed in the steady state at the temperature around 300 K in order to obtain stable results. Measurement setup with the sensing open stub and the container with the MUT are presented in Fig. 8. The container, shown in Fig. 8, inserts itself a negligible frequency shift.

Transmission coefficient ($S_{21}$) of the proposed structure is measured using the Agilent Technologies Network Analyzer N5227A. Several materials were tested: air, gasoline (medical), paraffin oil and sunflower oil, as well as water and ethanol. The measured $S_{21}$ parameters in both cases are presented in Figures 9, 10 and 12, respectively.

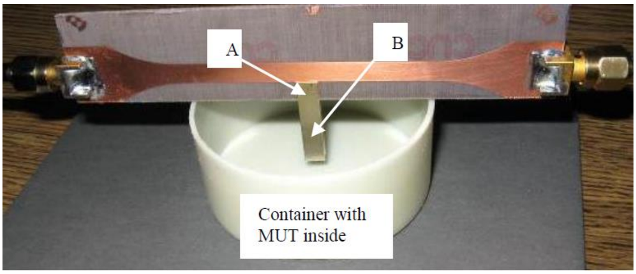



**Fig. 8** Measurement setup with the sensing open stub and the container. A - Segment of the stub printed on the substrate; B - Segment of the stub without the substrate to be immersed into the MUT

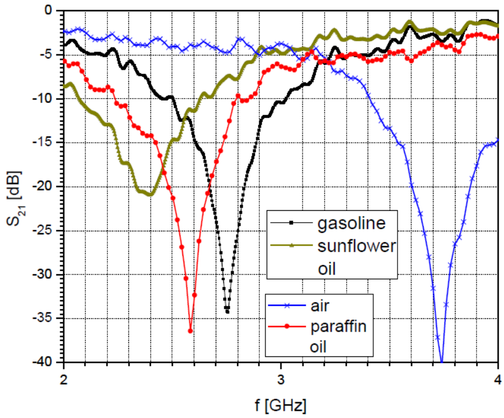



**Fig. 9** Measured $S_{21}$ coefficient of various MUT

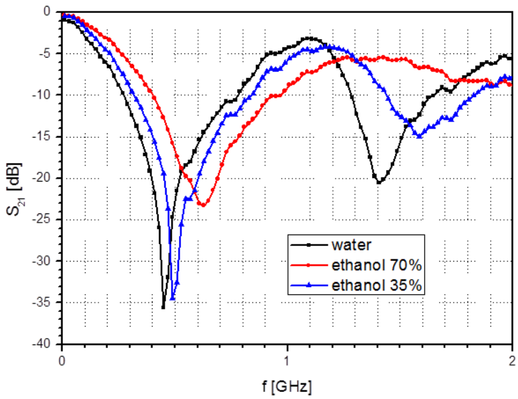



**Fig. 10** Measured $S_{21}$ coefficient of water and Ethanol

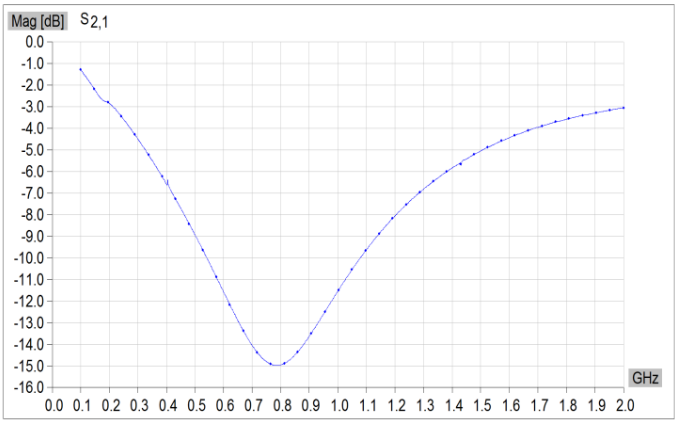



**Fig. 11** Ethanol 96% simulated $S_{21}$ coefficient (parameters from [17])

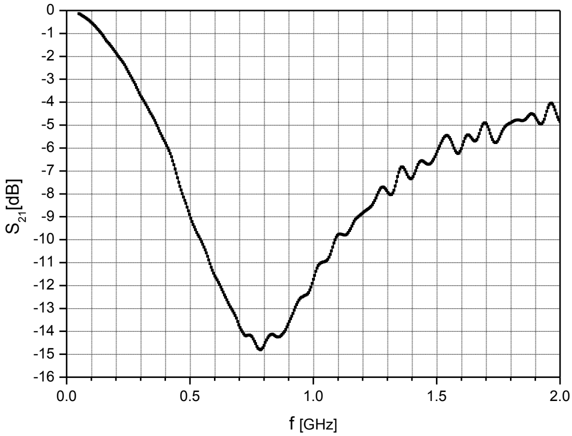



**Fig. 12** Ethanol 96% measured $S_{21}$ coefficient

According to the diagrams presented in Fig. 6. and Fig. 7. $\varepsilon_{r\text{-}MUT}$ values (and measured resonant frequencies) are: gasoline-medical (2.755 GHz) $\varepsilon_r = 1.90$; paraffin oil (2.584 GHz) $\varepsilon_r = 2.16$; sunflower oil (2.4 GHz) $\varepsilon_r = 2.5$; water (0.449 GHz) $\varepsilon_r = 73$; diluted ethanol 35% (0.49 GHz) $\varepsilon_r = 61$; ethanol 70% (Ethanol 70% v/v) (0.629 GHz) $\varepsilon_r = 37$ and ethanol 96% (Ethanol 96% v/v) (0.787 GHz) $\varepsilon_r = 22$. For the air (3.74 GHz), $\varepsilon_r = 1$. All results reasonably match values from the available references [17-21] as shown in Table 1. Agreement between simulation and measurement can be tested by comparing $S_{21}$ parameters for ethanol 96% from the simulation in Fig. 11 and from the measurement in Fig. 12.

The loss tangent tan(δ) is extracted (-3dB frequency range) according to [22] using the relation for the quality factor $Q \cong 1/\tan(\delta)$ and contribution of the MUT part in the entire electrical length of the open stub. The authors assume that tan(δ) of the CuClad 217 substrate as well as tan(δ) of the rigid metal strips in the air are negligible comparing to the tan(δ) of the MUT. Proposed estimation gives somewhat higher tan(δ) of the MUT (conservative version). The tan(δ) of the MUT is estimated from the influence of the MUT on the resonator and is slightly higher than the measured tan(δ) (only the longer part of the open stub is in the MUT).

$$\tan(\delta)_{mut} = \tan(\delta)_{meas}\left(1+\frac{d_{shorter}\sqrt{\varepsilon_{reff}}}{d_{mut}\sqrt{\varepsilon_{mut}}}\right) \quad (2)$$

**Table 1** Results

| MUT | Measured $\varepsilon_r$ | ($f_R$) | tan(δ) | Reference | $\varepsilon_r$ (error %) | tan(δ) (error %) |
|---|---|---|---|---|---|---|
| Gasoline-medical | 1.90 ±0.003 | (2.755 GHz) | 0.015 | [18] | 2.0 ( 5. %) | 0.015 ( 1. %) |
| Paraffin oil | 2.16 ±0.018 | (2.584 GHz) | 0.013 | [19] | 2.2 ( 2. %) | |
| Sunflower oil | 2.50 ±0.005 | (2.4 GHz) | 0.08 | [20] | 2.56 ( 3. %) | 0.128 (38. %) |
| Water # | 73.0 ±3.8 | (0.449 GHz) | 0.05 | [21] | 76.0 ( 4.%) | 0.026 (90. %) |
| Ethanol 35% | 61.0 ±2.6 | (0.49 GHz) | 0.064 | [17] | 58.9 ( 4.%) | 0.07 ( 9. %) |
| Ethanol 70% | 37.0 ±1.2 | (0.629 GHz) | 0.186 | [17] | 39.5 ( 7. %) | 0.177 ( 5. %) |
| Ethanol 96% | 22.0 ±1.0 | (0.787 GHz) | 0.53 | [17] | 22.0 ( 1.%) | 0.5 ( 6. %) |

# Tap water – water from the regular water supply

## 5. Discussion

The sensor is tested for two dielectric constants and frequency ranges (oils and ethanol-water mixture). The frequency shift between two measured materials is close to the ratio of square roots of their relative dielectric constants $\varepsilon_r$ for both ranges. For example, the ratio between the air and the water resonant frequencies is around 8.3 and the ratio between square roots of the water and the air dielectric constants is around 8.5. For gasoline these ratios are 1.36 and 1.38, respectively. The sensing part of the open stub is relatively short (15.25 mm) and can be immersed into a small container.

The measurement errors are calculated according to the frequency step in the measurement process, Table 1. The measurement errors against values in references [17-21] are given in percentages [%]. The errors are high for tan(δ) of the sunflower oil and water due to not so fixed mixture content of the sunflower oil and water from the regular water supply (especially for tan(δ)). Relative sensitivity for both dielectric constant ranges, (1.5-3.0) and (20-80), are given in Fig. 13 and Fig. 14, respectively. The resolution depends on the frequency step and on the dielectric constant range.

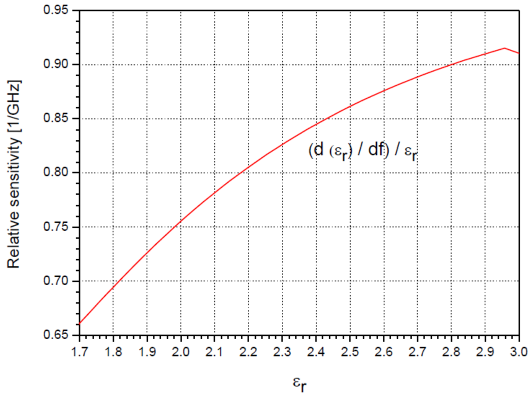



**Fig. 13** Relative sensitivity for the first specific range of the MUT relative dielectric constants (1.5–3.0) vs. dielectric constant

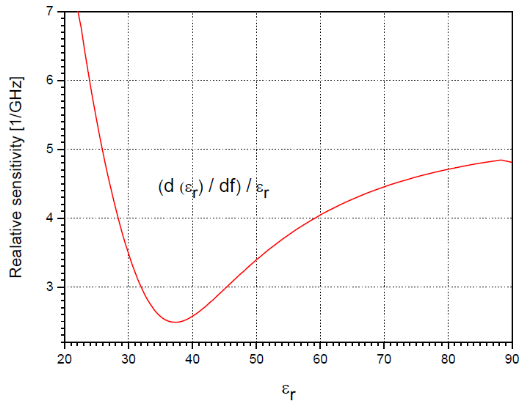



**Fig. 14** Relative sensitivity for the second specific range of the MUT relative dielectric constants (20–80) vs. dielectric constant

The second group of resonant frequencies in Fig. 10 is from the second resonant bandgap from the open stub (3 times the first resonance). The second resonances are somewhat shifted and have wider bandgaps. The reason is lower dielectric constant and higher tan(δ) for higher frequencies [17, 21].

## 6. Conclusion

The paper introduces the new type of a microwave resonant sensor realized as a T-junction with an open stub as a sensing part. The sensing part of the stub represents a pair of two metal strips in the form of a double-sided parallel-strip line without a substrate. The absence of the substrate enables each stub strip to be totally surrounded by the MUT. The frequency shift between two measured materials is close to the ratio of the square roots of their relative dielectric constants $\varepsilon_{r\text{-}MUT}$.

The proposed sensor is fabricated in the planar technology without dimension tolerance problems: narrowest line width is 3.5 mm that is much wider than typical photolithographic manufacturing tolerances (around 30 microns). The sensing open stub is short (15.25 mm), but still significantly longer than common tolerances. There are no additional technological processes such as vias, air-bridges, defected ground structures (DGS) or great number of vias like in substrate integrated waveguide (SIW) technology. The only additional process is bonding of the rigid metal strips to the microstrip line on the substrate.

The sensing stub can be simply immersed into the MUT without any additional preparing or use of auxiliary structures like cavity. The sensor is suitable for distinguishing the MUT, especially mixture concentrations such as water and ethanol mixture. Presented sensor is tested for two dielectric constant ranges: oils (1.5-3) and ethanol-water mixtures (20-80), and in two frequency ranges: around 2 GHz and below 1 GHz, respectively. In both cases frequency shift between two measured materials is closely proportional to the ratio of the square roots of their relative dielectric constants. All results reasonably match values from the available references.

**Acknowledgment**: *The authors would like to thank colleagues M. Pesic, N. Tasic, Lj. Radovic, N. Popovic and P. Manojlovic from the Institute IMTEL for their help in the realization and to professor M. Potrebic from the University of Belgrade, School of Electrical Engineering, for her assistance in performing the measurements.*

*This work was funded by the Serbian Ministry of Education and Science within the project TR 32008.*

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