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A Miniaturized Metamaterial Resonator-based Microwave Biosensor with High Quality Factor for Solid Materials Characterization

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Because of its qualitative importance in several aspects, especially biomedical ones, the characterization of solid materials has recently attracted the interest of scholars. The detection of such a material based on its dielectric constant with reliable precision represents the main desired objective. In this paper, a miniature sized microwave biosensor is presented for solid materials characterization. The proposed biosensor is formed by two identical and periodic split ring metamaterial resonators (SRRs) fed by a microstrip line adapted to its two extremities. The method proposed for the design of our biosensor is based on the exploitation of the electromagnetic qualities of each SRR representing the unit cell of the overall structure. The size of the SRR is optimized for electrical dimensions of $0.251\lambda_0 \times 0.2251\lambda_0 \times 0.031\lambda_0$ where λ_0 is the free space wavelength calculated at the lowest operating frequency of 4.72 GHz. the characterization of solid materials is based on the detection of its dielectric constants through direct contact with the proposed biosensor. For our study, we have used four different substrates to have the different sensitivities. The simulations carried out on the overall structure (biosensor and dielectric substrate) based on the HFSS numerical simulator showed good sensing performance of our biosensor. A low full width at half maximum ($FWHM = 0.004$), A high quality factor ($Q = 103.28$) and a high figure of merit ($FOM = 428.61$). These features can make our biosensor more reliable for solids materials sensing.

Keywords: Biosensor, Dielectric constant, Metamaterial, Quality factor, SRR.

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1. INTRODUCTION

Identifying the physical and biological characteristics of materials has become necessary nowadays for uses in several fields. Generally speaking, the detection of samples and species amounts to the search for methods and techniques to determine the dielectric constant (permittivity) of such a structure. Common methods for detecting materials support the use of sensors of all kinds. The use of conventional sensors has revealed several shortcomings such as their low sensitivities, their modest quality factors, their relatively long analysis times and above all their considerable sizes which are not suitable for low-volume species. By delving into the type and quality of sensors, most research has proven that the design material itself is one of the most important influencing factors [1]. In the last few years, sensors designed based on metamaterials [2–5], commonly called biosensors, have proven their effectiveness in obtaining small planar detection structures intended for the identification of electromagnetic properties in different frequency bands. Biosensors that are based on metamaterial resonators [6] are generally operated according to the principle of disturbance of electromagnetic fields [7]. Direct contact of the materials under test (MUT) with the biosensor can create a shift in resonance frequencies, which in one way or another facilitates the calculation of dielectric constants. In this context, the design of biosensors based on SRRs has taken most of the interest in recent studies. In [8], a dual-band biosensor was suggested for sensing applications at THz frequencies. The proposed device had a remarkable sensitivity of 304 GHz/RIU and 912 GHz/RIU from 0.1 to 3 THz. An absorber designed from folded metamaterial resonators is proposed in [9] for C- and Ku- band detection applications. The proposed absorber has been used as a miniaturized size biosensor with a sensitivity of 4.62%. Other types of biosensors of different shapes and sizes have been reported in [10–13] for detection applications in the Giga and Terahertz regions.

In this paper, a small metamaterial biosensor is proposed for the characterization of solid materials. The

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sensing mechanism is based on the principle of disturbance of electromagnetic fields in MUTs. When this principle is justified, shifts in resonance frequencies are easily obtained even for small sample sizes. On the other hand, the electromagnetic coupling of the two SRRs forming the biosensor with the microstrip line makes it possible to have the desired sensitivities. The proposed model allowed us to identify all MUTs with a high sensitivity of 4.15% and a quality factor of 103.28.

2. MATERIALS AND METHODES

2.1 Biosensing Principle

The proposed biosensor model is based on the principle of disturbance of the electromagnetic field by direct contact with the material under test MUT. Our biosensor is a planar structure (patch and substrate) which is very sensitive in nature to small variations in parameters. In addition, its miniature size makes it able to identify all the physical characteristics of the electromagnetic field propagating in the structure. This filed is perpendicular to the direction of propagation (field contained in the plane of the rings which is (OXY)). Consequently, the MUT will be able to create a strong disturbance of the transmission (S_{21}) of the resonators which translates the propagation of the electromagnetic wave (EM) through the biosensor. At this time, a shift in the resonant frequencies is observed. The frequency shifts in the overall structure (biosensor and MUT) is given by equation (1) [14].

$$\frac{\Delta f_r}{f_r} = \frac{\int_v (\Delta\varepsilon \vec{E}_0 \vec{E}_1 + \Delta\mu \vec{H}_0 \vec{H}_1) dv}{\int_v (\Delta\varepsilon |\vec{E}_0|^2 + \Delta\mu |\vec{H}_0|^2) dv} \quad (1)$$

On the disturbance volume v, Δf_r is the variation of resonant frequency f_r, $\Delta\varepsilon$ and $\Delta\mu$ are the variations of permittivity and permeability, respectively. $\vec{E}_0$, $\vec{H}_0$ are the electric and magnetic fields without samples and $\vec{E}_1$, $\vec{H}_1$ are the electric and magnetic fields in presence of samples.

2.2 Biosensor Description

The cell representing the biosensor is constituted by a copper patch printed on the upper face of the Rogers RT/duroid 5880 substrate with a dielectric constant of 2.2 and a thickness of 1.5 mm. The geometric shape of the patch of one SRR has several capacitive gaps to reinforce the electromagnetic coupling of the biosensor.

The proposed planar biosensor is formed by two metamaterial resonators SRRs have been feeded by matched microstrip line with a width $d = 1.8$ mm. The spacing between the two SRRs and the microstrip line is $e_1 = 0.8$ mm. The main parameters of the biosensor are characterized by equation (2).

$$\begin{cases} L = 2(a + S_3) \\ W = 2(b + e + S_4) + d \\ g_1 = g_2 = g_3 = g_4 = g_5 = g_6 \end{cases} \quad (2)$$

The SRR metamaterial resonator representing the biosensor is shown in Fig. 1.

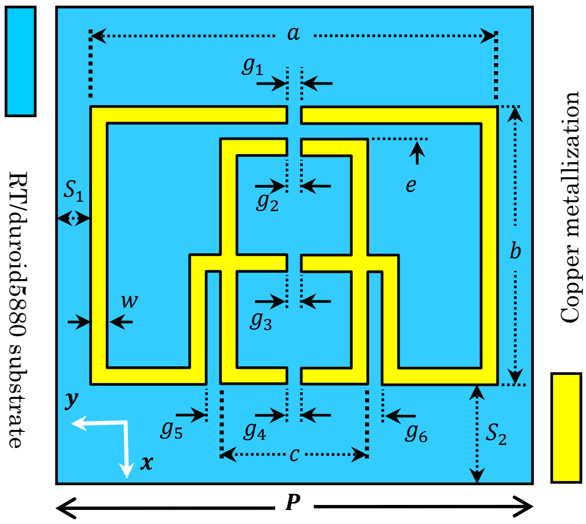


Fig. 1 – Geometric layout of the metamaterial basic cell

The overall configuration with two proposed SRRs and the microstrip line is shown in Fig. 2.

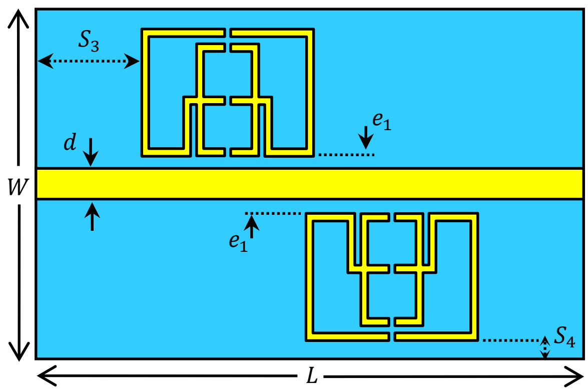


Fig. 2 – Proposed planar biosensor

The dimensions of the SRR of period $P = 16$ mm are listed in Table 1.

Table 1 – Dimensions of various CU-SRR parameters

Parameter	Value (mm)
a	12
b	8
c	5
w	0.5
e	0.5
g_1	0.5
S_1	2
S_2	4

3. RESULTS AND DISCUSSION

3.1 SRR Transmission

To obtain the spectral response of the proposed SRR, we set the boundary conditions; the electromagnetic wave is perpendicular to the planes of equations $z = n$. The simulation arrangement is shown in Fig. 3.

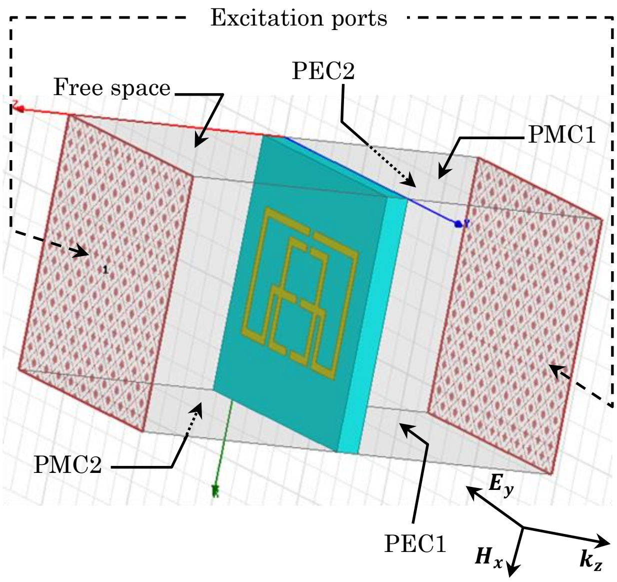


Fig. 3 – Simulation arrangement of the SRR cell

The transmission of the proposed SRR obtained by the numerical calculations is represented in Fig. 4.

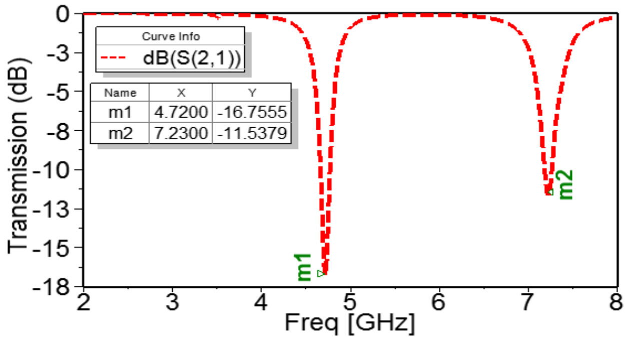


Fig. 4 – Transmission of the proposed SRR

As shown in Fig. 4, the proposed SRR has a dual-band stop-band behavior for two C-band resonances. For the lower frequencies the resonance is 4.72 GHz and for the higher frequencies the resonance is 7.23 GHz for both transmissions of 16.75 and 11.53 dB, respectively.

3.2 Biosensor Performance Analysis

The main objective of the design of the biosensor based on the two SRRs is to detect the dielectric constant of the material under test MUT. The proposed model consists of placing the MUT on top of the biosensor, therefore direct contact with the substrate and the patch. This contact allows the electromagnetic field to be disrupted in the structure composed of the biosensor and the MUT, which causes a shift in the resonance frequencies without having to increase the dimensions of the biosensor. With a coupling spacing $\boldsymbol{e_1}$ = 0.8 mm, the portions $\boldsymbol{S_3}$ = 6 mm and $\boldsymbol{S_4}$ = 2.3 mm, the biosensor area is (36 × 24) mm^2. The proposed biosensing model (biosensor + MUT) is shown in Fig. 5.

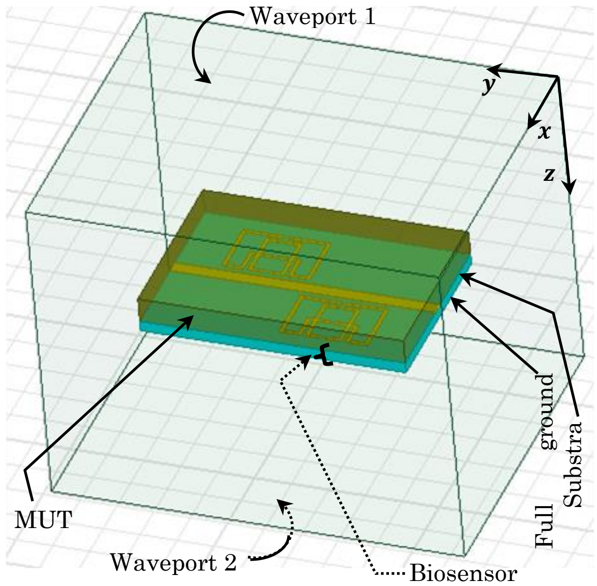


Fig. 5 – Biosensor model based on CU-SRRs

The resonance frequency depends on the capacitance of the SSR metamaterial resonator according to the expression [15].

$$f_0 = \frac{1}{\sqrt{2\pi(L_{SRR} \times C_{SRR})}} \qquad (3)$$

When adding the MUT to biosensor, the overall capacitance of the structure is modified, so the resonance is shifted and calculated by the following expression [15].

$$f_1 = \frac{1}{\sqrt{2\pi[L_{SRR} \times (C_{SRR} + C_{MUT})]}} \qquad (4)$$

For our study, we have chosen four materials with different permittivities (values ranging from 2.55 to 3.5) and for the same thickness h' = 3.5 mm. The materials under test are Taconic TLX (ε_r = 2.55, $tg\delta$ = 0.0019), Taconic TLE (ε_r = 2.95, $tg\delta$ = 0.0028), Taconic TLC (ε_r = 3.2, $tg\delta$ = 0.003) and Taconic RF-35 (ε_r = 3.5, $tg\delta$ = 0.0018). Each MUT is placed on the planes of equations z = 1.535 mm. The transmission coefficients of the overall model, for the two resonances are represented in Fig. 6.

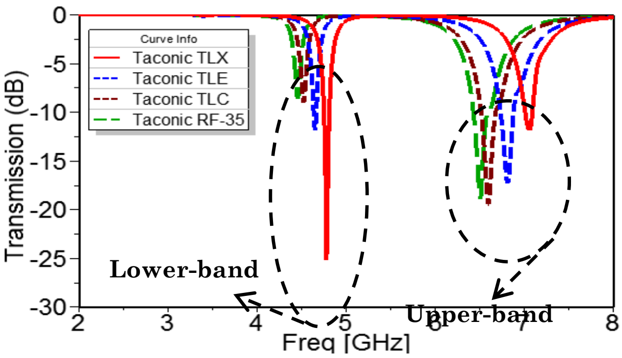
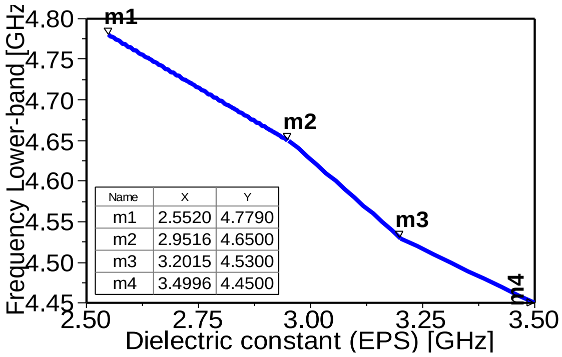
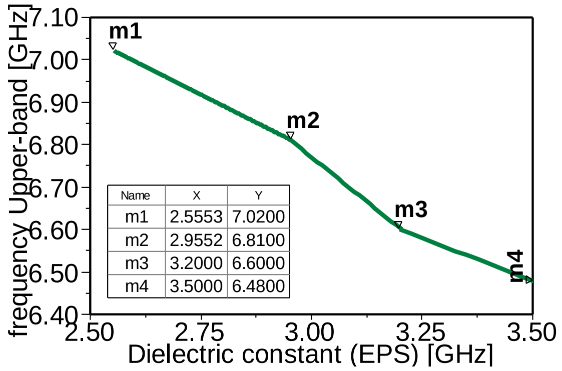


Fig. 6 – Transmission of different MUT with Frequency shift

The sensitivity characteristics for both bands are represented in Fig. 7.



a)



b)

Fig. 7 – Sensitivity for: (a) Lower and, (b) Upper-band

According to the transmission coefficients of the biosensor (when in direct contact with the MUT) shown in Fig. 7, we observe a red shift of the resonance peaks when the permittivity of the MUT increases. This feature is justified by Eq (4) whose resonance is inversely proportional to the dielectric constant and the capacitor. The sensitivities extracted from these characteristics are defined by equation (5) [16].

$$S(\%) = \frac{f_1 - f_0}{f_0(\varepsilon_r - 1)} \times 100 \quad (5)$$

f_1 is the frequency when the material is attached to the biosensor and f_0 is the resonance frequency of the SRR (4.72 GHz for the lower-band and 7.23 GHz for the upper-band), respectively. Fig. 7 (a) and (b) show the sensitivity of the biosensor for the lower and upper bands. The parameters extracted from these two graphical features are indicated in Table 2.

The parameters cited in Table 2 show that the sensitivities at the upper resonant frequency are significant compared to those corresponding to the lower resonant frequency. In this upper band, the biosensor has significant transmissions (more than 15 dB), which justifies the maximum sensitivity of around 4.15% (for a small permittivity variation $\Delta\varepsilon_r = 1.3$).

To validate the results obtained, the performance of our biosensor can be checked by other characteristics such as the quality factor (Q), the full width at half maximum ($FWHM$) and the figure of merit (FOM). These characteristics are given by [17].

Table 2 – Sensing performances of the biosensor

MUT sensing	Frequency shift (MHz)	
	Lower-band	Upper-band
Rogers RT and Taconic TLX	60	210
Rogers RT and Taconic TLE	70	420
Rogers RT and Taconic TLC	190	630
Rogers RT and Taconic RF35	270	750
MUT sensing	Sensitivity (%)	
	Lower-band	Upper-band
Rogers RT and Taconic TLX	0.82	1.87
Rogers RT and Taconic TLE	0.76	2.98
Rogers RT and Taconic TLC	1.83	3.96
Rogers RT and Taconic RF35	2.28	4.15

$$\begin{cases} Q = \frac{f_0}{\Delta f_{\mp 3dB}} \\ FWHM = \frac{\lambda}{Q} \\ FOM = S \times Q \end{cases} \quad (6)$$

Here, Δf denotes the +3 dB bandwidth calculated at 70.71% of the transmission and λ is the wavelength calculated at lower and upper-band. For the maximum sensitivity of 4.15 obtained at the upper frequency of 7.23 GHz, the characteristics of the biosensor are, $Q = 103.28$, $FWHM = 0.004$ and $FOM = 428.61$.

Generally, a high performance biosensor has a high quality factor, a small $FWHM$ and a considerable FOM, which is justified for our proposed biosensor.

4. CONCLUSIONS

To sum up, a compact biosensor with a high quality factor is present in this paper for solid materials sensing applications. The proposed biosensor is formed by two SRRs metamaterial resonators coupled to a microstrip line of length of the order of 36 mm. The MUT permittivity detection model is based on the principle of disturbance of electromagnetic fields by direct contact. The compact size of the structure has contributed significantly to the shift in resonant frequencies. The four MUT chosen for the detection have permittivities varied between 2.55 and 3.5. Direct contact of the MUTs with the biosensor made it possible to disrupt the electromagnetic field inside each material under test. According to the obtained results, our biosensor has remarkable sensing qualities such as a high quality factor of 103.28, a sensitivity of around 4.15% even for small MUTs, a FWHM of low value and a FOM of significant value of 428.61.

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Мініатюрний мікрохвильовий біосенсор на основі метаматеріального резонатора з високим коефіцієнтом якості для характеристики твердих матеріалів

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Через свою якісну у значимість у багатьох галузях, особливо біомедичних, характеристика твердих матеріалів нещодавно привернула інтерес вчених. У цій статті представлено мікрохвильовий біосенсор мініатюрного розміру для визначення характеристик твердих матеріалів, який утворений двома ідентичними та періодичними метаматеріальними резонаторами з розділеним кільцем (SRR), що живляться мікросмужковою лінією, адаптованою до двох її кінців. Метод, запропонований для розробки нашого біосенсора, базується на використанні електромагнітних якостей кожного SRR, що представляє елементарну комірку загальної структури. Розмір SRR оптимізовано для електричних розмірів 0.251 $\lambda_0 \times$ 0.2251 $\lambda_0 \times$ 0.031λ_0, де λ_0 – довжина хвилі вільного простору, розрахована на найнижчій робочій частоті 4,72 ГГц. Характеристика твердих матеріалів заснована на виявленні їх діелектричної проникності через прямий контакт із запропонованим біосенсором. Для нашого дослідження ми використовували чотири різні підкладки, щоб мати різну чутливість. Моделювання, проведене на загальній структурі (біосенсора та діелектричної підкладки) на основі чисельного симулятора HFSS, показало хороші характеристики чутливості нашого біосенсора. Низька повна ширина на половині максимуму (FWHM = 0,004), високий коефіцієнт якості (Q = 103,28) і висока добротність (FOM = 428,61). Ці функції можуть зробити наш біосенсор більш надійним для визначення твердих речовин.

Ключові слова: Біосенсор, Діелектрична проникність, Метаматеріал, Добротність, SRR.