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1st International Conference on Trends in Advanced Research
March 4-7, 2023 : Konya, Turkey

ICTAR

Modeling of a New H-C Shape Non-Periodic Metamaterial Resonator (HC-SRR) for Multi-band Applications

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Abstract – Multi-band structures contribute in one way or another to the miniaturization of microwave circuits. These structures have the advantage of providing the same electronic function for different frequency bands and for a single compact circuit. In this work, a new metamaterial resonator is modeled for multi-band applications. The proposed structure is a non-periodic split-ring resonator of H-C shape (HC-SRR). The copper patch of the HC-SRR is printed on the upper side of the used dielectric substrate which is Rogers RO 4003 of physical characteristics (ε_r =3.55 and $tg\delta$ =0.0027). The electrical dimensions of the HC-SRR basic cell are optimized at (0.41λ_0 ×0.42λ_0), where λ_0 is the free space wavelength calculated at the lowest operating frequency which is 8.22 GHz. The HC-SRR is modeled based on its equivalent electrical circuit containing the ($L_s - C_s$) series branches. Other physical characteristics of the proposed resonator are obtained such as permeability and electric field to justify the impact and efficiency of HC-SRR for multi-band applications.

Keywords – Electromagnetic Field, Equivalent Electrical Circuit, HFSS, Metamaterial, Multi-Band, Permeability.

I. INTRODUCTION

Frequency responses for different bands require the design of multiple electronic circuits integrated into the same device. As a result, the size of the circuits will be larger, which represents a huge constraint. In microwave regime, the frequency shift causes a remarkable change in the dimensions of such a circuit. To ensure the desired miniaturization, it is necessary to seek another means or another technique. Recently, the exploitation of the unusual physical characteristics of metamaterials has contributed to the miniaturization of electronic circuits in the microwave regime without having frequency shifts [1−3].

The split ring metamaterial resonator (SRR) designed for the first time in 1999 by Sir J. Pendry [4] represents a structure able of reacting with electromagnetic waves propagating for too small wavelengths [5]. The main characteristic of this type of resonator is the possibility of having negative permittivity or permeability or both at the same time [6, 7]. This characteristic is represented by the left hand mediums (ENG, MNG) and the composite right hand left hand mediums often called double negative mediums (DNG) [8−10]. The SRR has shown its effectiveness for a large number of microwave circuits such as filters [11−15], antennas [16.17], absorbers [18, 19], sensors [20], etc.

In this work, we present a new type of metamaterial resonator. The proposed HC-SRR is formed by a copper patch containing four H-segments coupled to two C-segments. The modeling of the basic cell is obtained based on the equivalent electric circuit which contains $(L_s - C_s)$ series branches and adapted to the impedance of 50 Ω. the main objective of this work is to validate all the physical characteristics of the proposed HC-SRR based on the multi-band frequency response for the equivalent circuit model and response calculated by the used simulator.

II. Evolution of the Proposed HC-SRR

A. Basic cell configuration

The split ring metamaterial resonator is a microwave structure with magnetic activity that has unusual physical characteristics. The first proposed SRR is the circular shaped resonator formed by two internal and external rings. The proposed resonator patch is formed by four identical H-shaped segments (two in horizontal plane and two others in vertical plane) coupled to two other identical C-shaped segments. The global patch is printed on the upper side of the Rogers RO 4003 substrate with a thickness h of order of 1.65 mm. The proposed metamaterial resonator of HC-SRR patch is shown in Fig. 1.

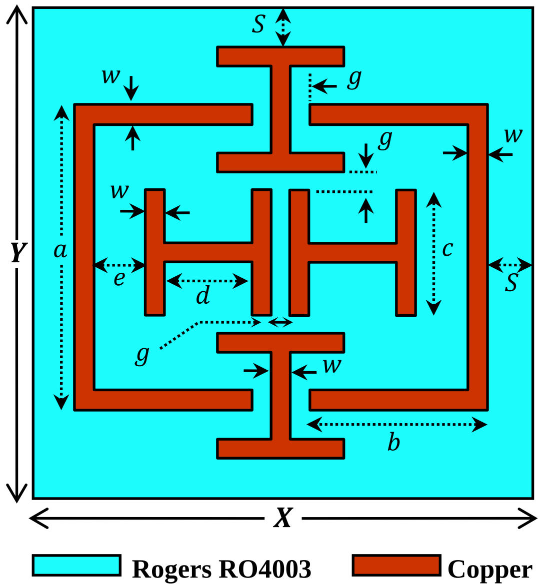

Fig. 1. Geometry layout of the proposed HC-SRR

B. Dimensions

The sides (X, Y) of the proposed HC-SRR are given by the following expression.

$$\begin{cases} X = g + 2(d + e + S) + 3w = 2(b + g + S) + w \\ Y = 2(S + g) + 3c = a + c - w + 2S \end{cases} \tag{1}$$

The dimensions of the basic cell are summarized in Table 1.

Table 1. Various parameters of the HC-SRR basic cell

Parameter	Value (mm)	Parameter	Value (mm)
a	9.5	g	0.5
b	6	w	0.5
c	4	S	1
d	3	X	15.5
e	2	Y	15

III. Results and Discussion

A. Simulation setup of the basic cell

For the simulation setup of our resonator, we have introduced the necessary band conditions which are fixed according to the electromagnetic field ($\boldsymbol{E}$ and $\boldsymbol{H}$) propagating in our resonator. Therefore, the electric field must be perpendicular to the vertical gaps of the inner ring of the resonator on the two surfaces of the ray box (PEC1 and PEC2). The magnetic field must be perpendicular to the plane of the two rings constituting the resonator (PMC1 and PMC2) and the two wave ports are maintained in such a way that $\boldsymbol{k} \perp \boldsymbol{E}$ and $\boldsymbol{k} \perp \boldsymbol{H}$, as shown in Fig. 2.

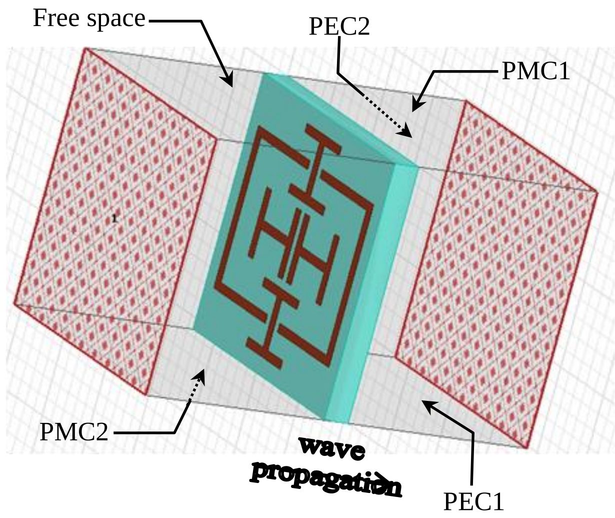

Fig. 2. HC-SRR boundary conditions

B. Frequency response

After applying boundary conditions, the HC-SRR frequency response is represented in Fig. 3.

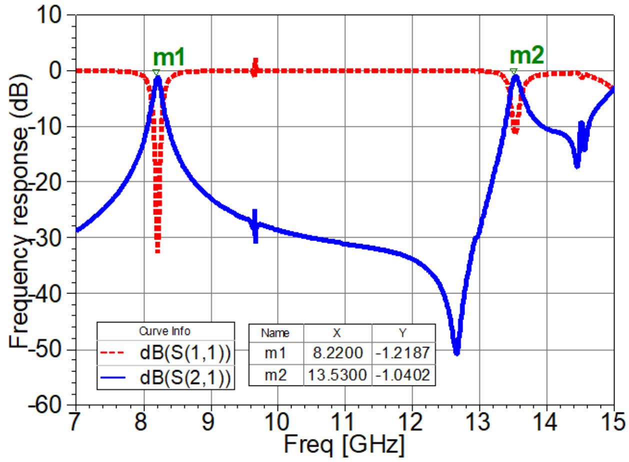

Fig. 3. Frequency response of the proposed HC-SRR

The simulation on the frequency range [7−15] GHz, allows us to represent the reflection and the transmission coefficients of the proposed HC-SRR. In Fig. 3, we note that the behavior of the resonator is band-pass for two resonances. At the first resonance of 8.22 GHz, the insertion losses (IL) are of the order of −1.21 dB. For the second resonance of 13.53 GHz, These losses are −1.04 dB. So the frequency response of our SRR covering the two X- and Ku- bands, respectively.

C. Effective permeability

In microwave regime, to extract the effective permeability of such a structure, Nicolson-Ross-Weir (NRW) method [21] is very popular. The effective permeability of the metamaterial resonator is related to its reflection and transmission. It is expressed by the following relation.

$$\begin{cases} \mu_{eff}(f) = \dfrac{2}{jkh}\dfrac{1-v_2}{1+v_2} \\ v_1 = |S_{21}| + |S_{11}| \end{cases} \qquad (2)$$

Where S_{11} and S_{21} represent the reflection and transmission coefficients, respectively and k is the ratio of frequency ω to the speed of light c_0. The effective permeability (for its two real and imaginary parts) of our proposed HC-SRR is shown in Fig. 4.

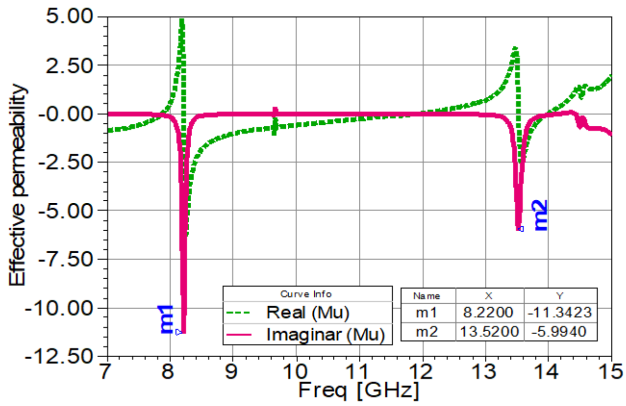

Fig. 4. Effective permeability of the proposed HC-SSR

As seen in Fig. 4, the imaginary part of the effective permeability of the proposed HC-SRR is close to zero except around the two resonances where the permeability takes negative values of −11.34 and −5.99 at the two resonances of 8.22 and 15.53 GHz, respectively. For the real part, we notice that the characteristic changes their sign around the two resonances of the HC-SRR. It can be concluded that the proposed HC-SRR has a (MNG) medium.

D. Electric field

To better understand the behavior of the proposed HC-SRR, we present in this section the mechanism of the propagation of incident electromagnetic waves inside the structure. Here, we present the distribution of the electric field $\boldsymbol{E}$. Fig. 5 shows this characteristic at two resonances, respectively.

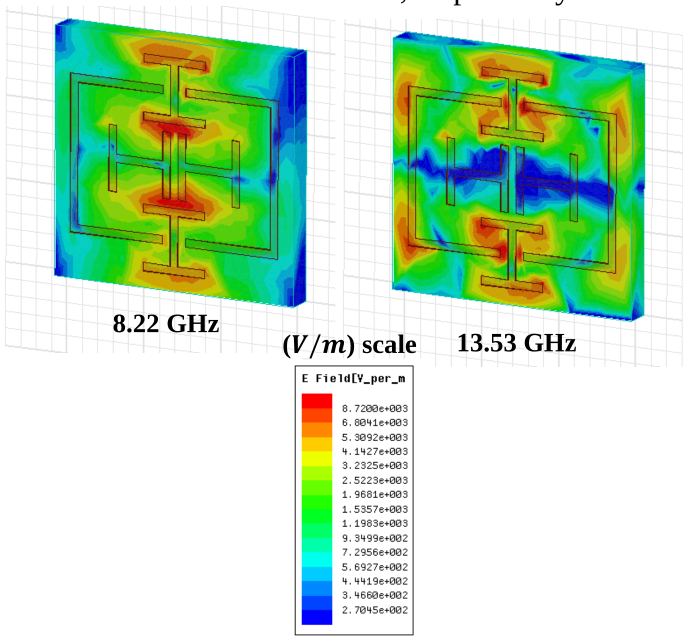

Fig. 5. Electric field distribution at two resonances with (V/m) scale of the proposed HC-SRR

As shown in Fig. 5, for the first resonance, the E-field is concentrated with relatively modest values around the capacitive gaps, whereas for the second resonance, the electric field propagates in all sides of the substrate. This capacitive effect justifies the creation of two resonances for different peaks.

E. HC-SRR modeling

In this section we seek to validate the results obtained previously based on the proposed electrical circuit model of the HC-SRR resonator. Generally, for the metamaterial structures designed with copper, the metallic strips form the inductances and the split gaps form the capacitances. The proposed HC-SRR consists of both inductive and capacitive constituents. The H and C-segments involved in the basic cell acted as inductors, whereas the opening ends within the metal created capacitors. Hence, a $(L_s - C_s)$ resonance circuit is formed in this resonator. Therefore, the resonance frequency can be extracted from Equation (3) [22].

$$f_r = \frac{1}{2\pi\sqrt{L_s C_s}} \tag{3}$$

The proposed equivalent circuit model of the HC-SRR resonator is shown in Fig. 6.

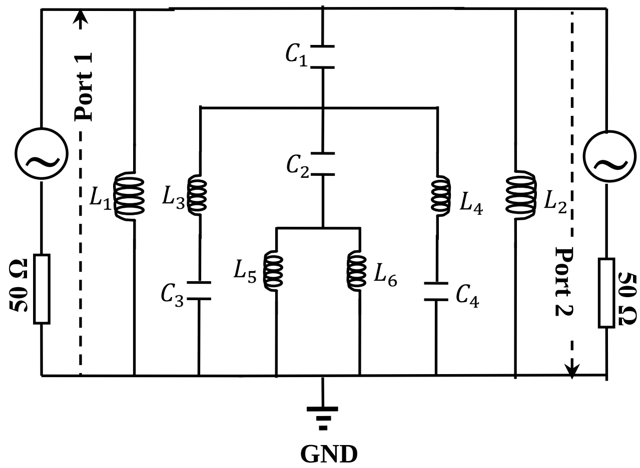

Fig. 6. Equivalent circuit model of the proposed HC-SRR

The inductors L_1 and L_2 on the one hand and the capacitors C_1 and C_2 on the other hand are the coupling inductors and capacitors in the structure of the patch.

The reflection coefficient s11 calculated from the HFSS and derived by the equivalent electrical circuit is shown in Fig. 7.

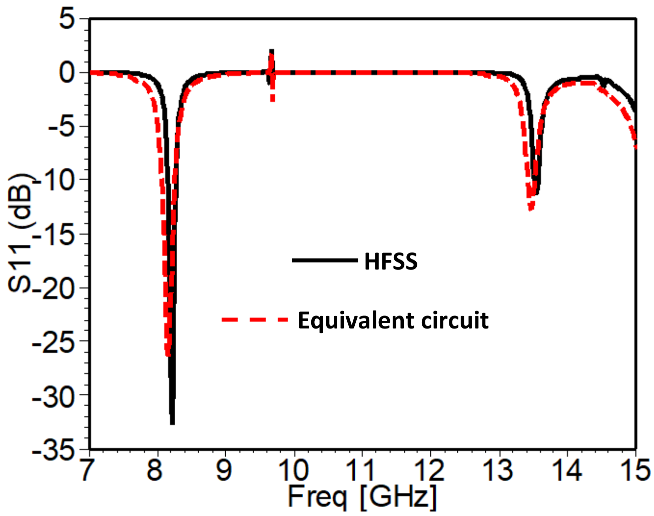

Fig. 7. S_{11} plot from HFSS and equivalent circuit

As shown in Fig. 7, the reflection coefficient of the proposed HC-SRR is represented by the numerical calculation and by the equivalent electrical circuit model. We note the frequency characteristic is almost the same, which can validate the electromagnetic qualities thus obtained previously.

IV. CONCLUSION

To sum up, a modeling of a new metamaterial resonator is presented in this work. The modeled resonator is an HC-shaped split ring type that has four H-segments and two C-segments. The simulation of the proposed HC-SRR shows a dual-band frequency response covering both X- and Ku-bands. The first resonance is observed at 8.22 GHz while the second one is located at 13.53 GHz. The equivalent electrical circuit model of the HC-SRR provides two frequency bands with the same numerically calculated resonances, which makes it possible to validate all the electromagnetic qualities obtained. The proposed HC-SRR represents a potential candidate for multi-band applications.

ACKNOWLEDGMENT

This work was supported by the Algerian Ministry of Higher Education and Scientific Research and the General Directorate of Scientific Research and Technological Development (DGRSDT) via funding through the PRFU under Project No. A25N01UN220120200001.

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