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REGULAR ARTICLE

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

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The multi-band structures have the advantage of providing the same electronic function for different frequency bands and for a single compact circuit. In this paper, a new metamaterial resonator was 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 tgδ = 0.0027). The electrical dimensions of the HC-SRR unit cell are optimized at ($0.374\lambda_0 \times 0.362\lambda_0 \times 0.039\lambda_0$), where λ_0 is the free space wavelength calculated at the lowest operating frequency which is 7.25 GHz. The HC-SRR is modeled based on its equivalent electrical circuit containing the ($L_S - C_S$) series branches. The obtained results show a dual-band bandpass behavior of our metamaterial resonator at both resonances of 7.25 and 9.31 GHz. This behavior was validated by the equivalent circuit model based on the reflection characteristic. Other physical characteristics of the proposed resonator are obtained such as constitutive parameters and electric field to show the unusual electromagnetic behavior of the proposed HC-SSR. Obtained negative values of permittivity and/or permeability can define the left hand medium (LHM) represented by our resonator. The study and analysis proposed in this work can justify the impact and efficiency of the proposed HC-SRR for multiband applications, especially for wireless communication devices.

Keywords: Constitutive parameters, Electric circuit model, Metamaterial, Reflection, Resonator.

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1. 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. In the past few years, 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].

The split ring metamaterial resonator (SRR) designed for the first time in 1999 by Sir J. Pendry [2] represents a structure able of reacting with electromagnetic waves propagating for too small wavelengths [3]. The main characteristic of this type of resonator is the possibility of having negative permittivity or permeability or both at the same time [4]. 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) [5-7]. The SRR has shown its effectiveness for a large number of microwave circuits such as filters [8-12], antennas [13, 14], absorbers [15, 16], sensors [17], etc.

In this paper, we present a new type of H-C shape 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 unit 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. For the analysis of the proposed HC-SRR, we based on its spectral response and constitutive parameters. The frequency characteristics of permittivity and permeability can reveal left-hand behavior LHM due to negative values around resonance frequencies. The physical characteristics of the proposed HC-SRR based on the multi-band frequency response are validated by the equivalent circuit model. The resonator reflection has been discussed by comparing its responses obtained by the different calculations.

The remaining sections of this paper are structured by presenting the unit cell evolution in section two, which includes configuration and dimensions. In section three, the parameters and performances of the proposed resonators are discussed. Finally, conclusions are included in section four for summarizing the paper.

2. EVOLUTION OF THE PROPOSED HC-SRR

2.1 Unit Cell Configuration

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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 inner and outer 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.

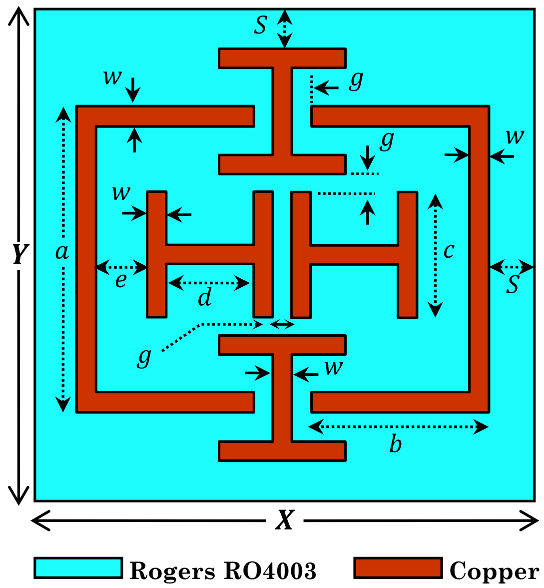

Fig. 1 – Geometric layout of the proposed HC-SRR

2.2 Dimensions

The proposed HC-SRR is a non-periodic metamaterial resonator. This type of structure is frequently used for microwave devices. The sides (***X***, ***Y***) of the proposed HC-SRR are given by the following expression.

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

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

Table 1– Geometric narration of the HC-SRR unit 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

The non-periodicity of the proposed resonator is justified by the geometric characteristic *X*≠*Y*.

3. RESULTS AND DISCUSSION

3.1 Simulation Setup of the Unit Cell

For the simulation setup of our resonator, we have introduced the necessary band conditions which are fixed according to the electromagnetic field (***E*** and ***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.

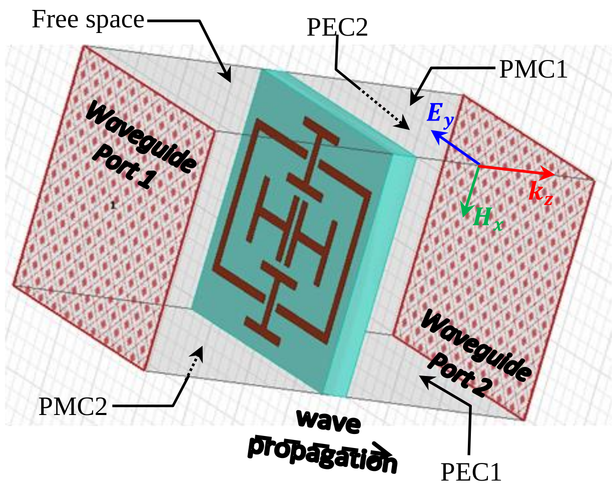

Fig. 2 – HC-SRR boundary conditions

3.2 Frequency Response

The frequency response of the HC-SRR resonator is represented by its reflection and its transmission. After applying boundary conditions, the HC-SRR reflection and transmission are represented in Fig. 3.

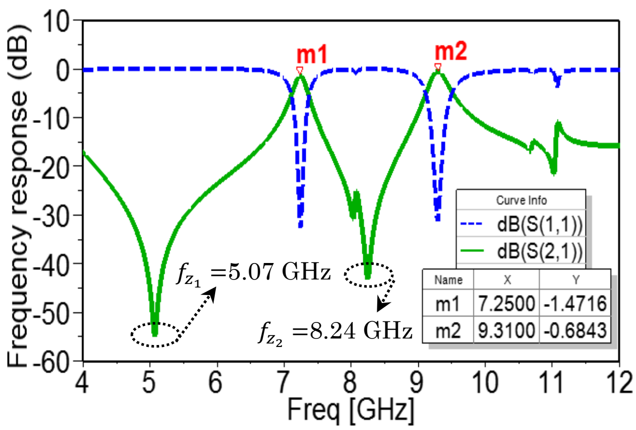

Fig. 3 – Frequency response of the proposed HC-SRR

The simulation on the frequency range [4-12] 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 7.25 GHz, the insertion losses (IL) are of the order of – 1.47 dB. For the second resonance of 9.31 GHz, These losses are – 0.68 dB. So the frequency response of our SRR covering the two C- and X-bands, respectively. Also, two frequencies of zero transmission of about – 54.83

and – 43.21 dB have been observed at 5.07 and 8.24 GHz, respectively.

3.3 Constitutive Parameters

In microwave regime, to extract the effective permittivity and permeability of such a structure, Nicolson-Ross-Weir (NRW) method [18] is very popular. Theses constitutive parameters are related to its reflection and transmission. They are expressed by the following relations.

$$\varepsilon_r = \frac{2}{\sqrt{\frac{\omega}{c} \times h}} \times \frac{1-(S_{21}+S_{11})}{1+(S_{21}+S_{11})} , \quad (2)$$

$$\mu_r = \frac{2}{\sqrt{\frac{\omega}{c} \times h}} \times \frac{1-(S_{21}-S_{11})}{1+(S_{21}-S_{11})} \quad (3)$$

Where $\omega = 2\pi f$, c is the velocity of light and $h = 1.65$ mm is the thickness of the used substrate. The real parts of the permittivity and permeability of the F-SRR are shown in Fig. 4.

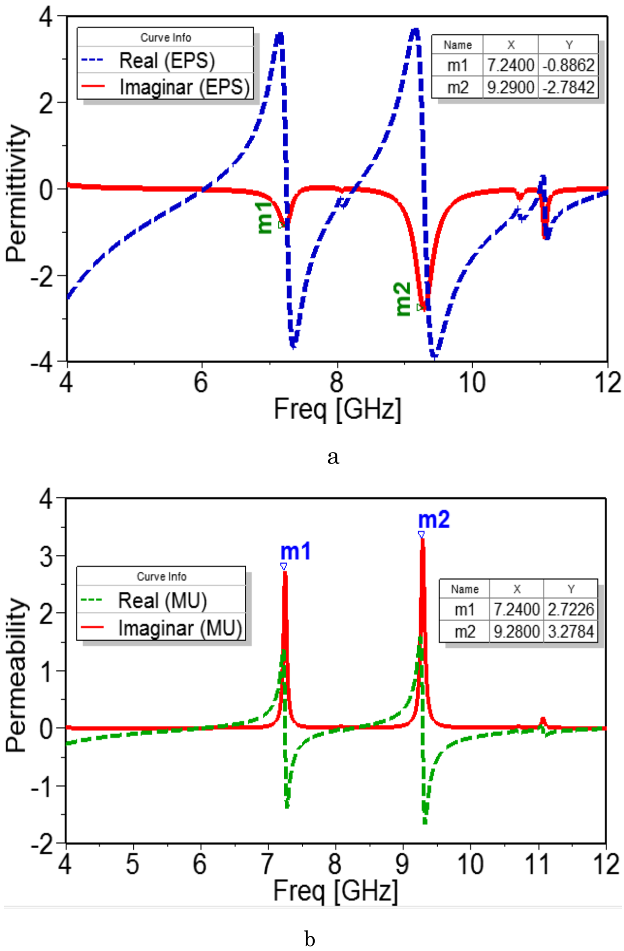

Fig. 4 – Constitutive parameters of the proposed HC-SRR: (a) Permittivity, (b) Permeability

As seen in Fig. 4 (a), the imaginary part of the effective permittivity of the proposed HC-SRR is close to zero except around the two resonances where the permeability takes negative values of – 0.88 and – 2.78 at the two frequencies of 7.24 and 9.29 GHz, respectively. For the real part, we notice that the characteristic changes their sign around the two resonances of the HC-SRR. In Fig. 4 (b), the imaginary part of the effective permeability is close to zero also, but around the HC-SRR resonances, the values of imaginary parts are positives for 2.72 and 3.27 at 7.24 and 9.28 GHz, respectively. We also notice that the real part of the permeability changes its sign. For all these characteristics, it can be concluded that the proposed HC-SRR has a double negative mediums (DNG).

3.4 Electromagnetic Field and Surface Current in the HC-SRR

Generally, the behavior of such a metamaterial resonator can be analyzed by the physical characteristics of the incident electromagnetic wave EM propagating in the structure. The use of Maxwell's equations allows characterizing the interaction of the electric and magnetic fields with the HC-SRR at both resonances, which may explain the electromagnetic behavior in one way or the other. The instantaneous values of the electromagnetic field at each point of the resonator are obtained by using the Maxwell's and Helmholtz equations [19].

$$\nabla^2 \begin{cases} \boldsymbol{E} \\ \boldsymbol{H} \end{cases} + k^2 \begin{cases} \boldsymbol{E} \\ \boldsymbol{H} \end{cases} = 0 , \quad (4)$$

For previous simulation conditions, the Eq. (4) becomes for the electromagnetic field.

$$\begin{cases} \left(\frac{\partial^2}{\partial z^2} + k^2\right) E_y(z) = 0 \\ \left(\frac{\partial^2}{\partial z^2} + k^2\right) H_x(z) = 0 \end{cases} , \quad (5)$$

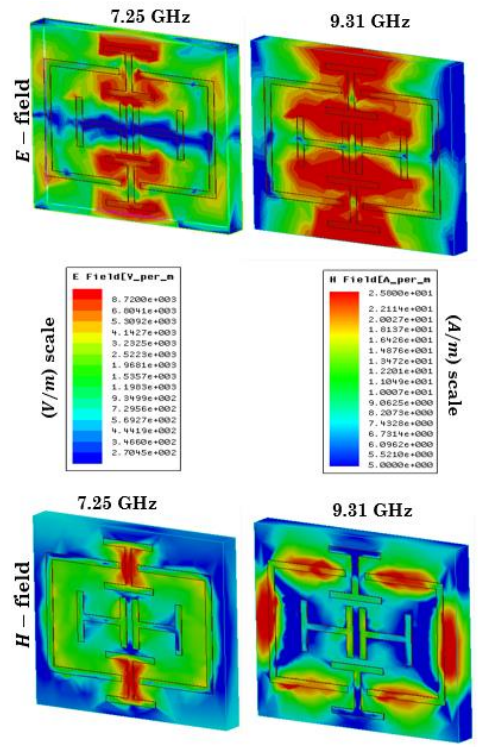

Fig. 5 –Electromagnetic field mapping in HC-SRR

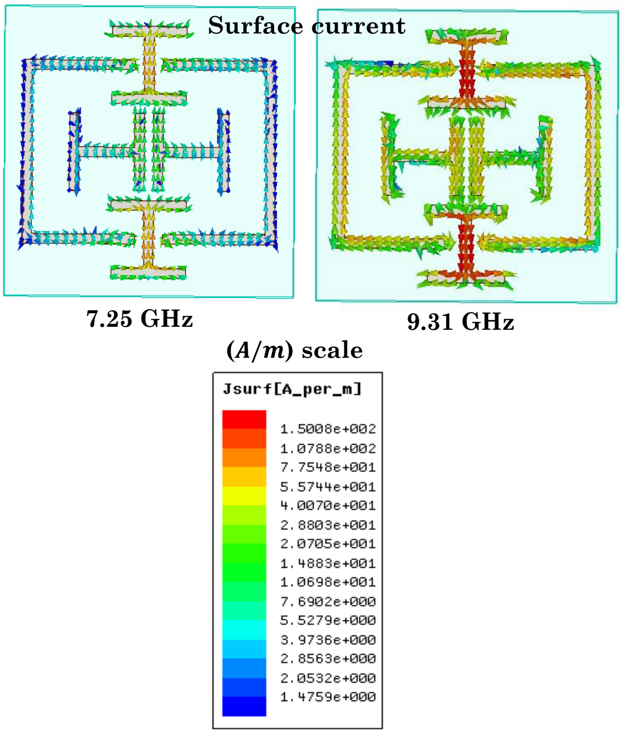

Fig. 6 – Surface current distribution on the HC-SRR

As shown in Fig. 5, for the first resonance of 7.25 GHz, the E field is concentrated with relatively modest values around the capacitive gaps, while for the second resonance of 9.31 GHz; the electric field propagates in all sides of the substrate with high concentration. This capacitive effect justifies the creation of the two resonances for different peaks. On the same figure, we can notice that the magnetic field is concentrated in the two segments in H in the horizontal plane for the first resonance, and in the two segments in *C* for the second resonance. This characteristic of the magnetic field can justify the orthogonality of the electromagnetic field in the HC-SRR resonator for the two resonances.

In Fig. 6, the surface current distribution on the patch resonator is shown for the same two resonances. For the first resonance, a low concentration of the current is observed on the patch, in particular for the two segments in *C*. For the first resonance, a low concentration of the current is observed on the patch, notably for the two *C* segments. For the second resonance, the surface current is distributed over the entire patch with significant values. We also note that the direction of the current in the patch for the two resonances is anti-parallel from one segment to the other, which directly contributes to the creation of the magnetic dipoles justifying the creation of the two clean resonances.

3.5 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 unit 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 Eq. (3) [20].

$$f_r = \frac{1}{2\pi\sqrt{L_s C_s}} \quad , \qquad (6)$$

The proposed equivalent circuit model of the HC-SRR resonator is shown in Fig. 7.

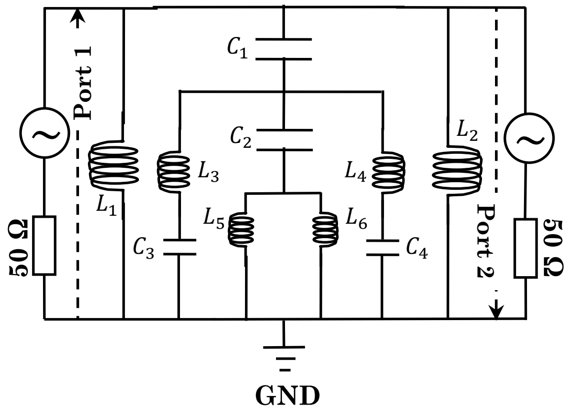

Fig. 7 – Equivalent circuit model of the HC-SRR

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 S_{11} calculated from the HFSS and derived by the equivalent electrical circuit is shown in Fig. 8.

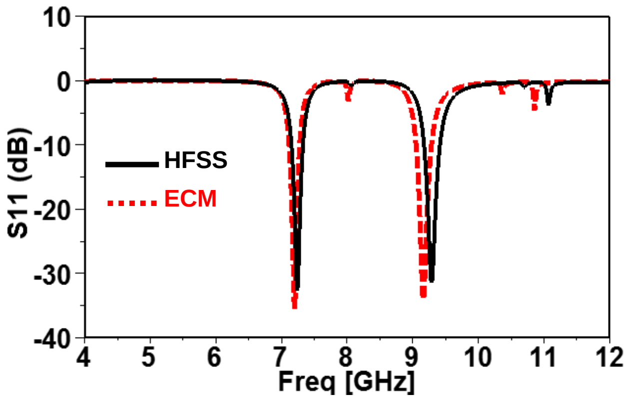

Fig. 8 – S_{11} plot from HFSS and equivalent circuit model

As shown in Fig. 8, 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.

4. CONCLUSIONS

In conclusions, a modeling of a new metamaterial resonator is presented in this paper. The modeled resonator has an *HC*-shaped split ring type that has four *H*-segments and two segments in *C*. The simulation of the proposed HC-SRR shows a dual-band frequency response covering both *C*- and *X*-bands. The first resonance was observed at 7.25 GHz while the second one is located at 9.31 GHz. the study of the constitutive parameters of the proposed resonator showed that it can represent a left-handed behavior because of the negative values of the permeability and the permittivity (real and/or imaginary parts) obtained around the resonances. 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 previously. The proposed HC-SRR represents a potential candidate for multi-band applications and wireless communication devices.

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Аналіз і моделювання нового неперіодичного метаматеріального резонатора (HC-SRR) форми H-C для багатодіапазонних застосувань

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Перевага багатодіапазонних структур полягає в тому, що вони забезпечують однакову електронну функцію для різних діапазонів частот і для однієї компактної схеми. У цій статті було змодельовано новий метаматеріальний резонатор для багатодіапазонних застосувань. Запропонована структура являє собою неперіодичний розщеплений кільцевий резонатор H-C форми (HC-SRR). Мідна нашивка HC-SRR надрукована на верхній стороні використаної діелектричної підкладки, яка має фізичні характеристики Rogers RO 4003 (ε_r = 3.55 and tgδ = 0.0027). Електричні розміри елементарної комірки HC-SRR оптимізовано за ($0.374\lambda_0 \times 0.362\lambda_0 \times 0.039\lambda_0$), де λ_0 — довжина хвилі вільного простору, розрахована на найнижчій робочій частоті, яка становить 7,25 ГГц. HC-SRR моделюється на основі його еквівалентної електричної схеми, що містить гілки серії (LS – CS). Отримані результати демонструють двосмугову поведінку нашого метаматеріального резонатора при обох резонансах 7,25 і 9,31 ГГц. Ця поведінка була підтверджена моделлю еквівалентної схеми на основі характеристики відбиття. Отримано інші фізичні характеристики запропонованого резонатора, такі як конститутивні параметри та електричне поле, щоб показати незвичайну електромагнітну поведінку запропонованого HC-SSR. Отримані негативні значення діелектричної проникності та/або проникності можуть визначати ліве середовище (LHM), представлене нашим резонатором. Дослідження та аналіз, запропоновані в цій роботі, можуть обґрунтувати вплив та ефективність запропонованого HC-SRR для багатодіапазонних застосувань, особливо для пристроїв бездротового зв’язку.

Ключові слова: Основні параметри, Модель електричного кола, Метаматеріал, Відбиття, Резонатор.