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REGULAR ARTICLE

Design of Miniaturized Dual-Band Bandpass Microstrip Filter Based on C-Shaped Metamaterial Resonators for RF/Microwave Applications

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In this article, a dual-band bandpass microstrip filter (DBBPF) is suggested and studied for RF/microwave applications. Our filter design method is based on two basic concepts; the use of metamaterial resonators in C-shaped split rings (C-SRR) to have the left-handed behavior (LH) with minimized losses and the feed by a microstrip line of significant length folded for the desired miniaturization. The two C-SRRs are optimized for a size of 6×3 mm² to cover the desired frequency bands and the two feed lines have a length of 37.1 mm to ensure the necessary adaptation. The search of a strong electromagnetic coupling between the two C-SRRs and the feed lines allowed us to choose the best position to place our resonators in the filter. The simulation of the filter parameters for two different proposed configurations shows two different qualities. According to the simulation outcomes for the two proposed filter configurations, two kinds of frequency response were obtained with different characteristics. For the first configuration where the two C-SRRs are separated by the folded arms of the two feed lines, the filter response is not clear. Contrary to that, the frequency response of the filter is desirable for the second configuration. The suggested filter which is represented by the second configuration has covered both bands (5.88 to 6.39 GHz and 10.75 to 11.16 GHz) for band-pass behavior. In addition, the analysis of the dispersion diagram allowed us to select the electromagnetic behavior associated with each band.

Keywords: Bandpass filter, Dispersion diagram, F-CSRRs, Metamaterial, Microwave frequencies

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1. INTRODUCTION

Microwave filters have contributed directly to the development of modern telecommunications systems and devices. The integration of such a filter into an electronic device comes down to the electrical qualities of the filter designed itself. To have compact circuits or devices, the use of multi-band filters [1, 2] becomes necessary. The major problem with the design of these filters is the congestion and interference [3] with other systems. To overcome this problem, scholars specializing in filtering have sought suitable solutions. At this level, the design material of the microwave filters becomes a key parameter for the majority of studies and research. Recently, metamaterials have attracted the attention of designers for having crucial qualities because of their unusual physical characteristics. The permittivity, permeability and refractive index of metamaterials (all three of which can have negative values) represent the main feature to miniaturize and minimize microwave filters [4-6]. Moreover, the resonance of SRRs metamaterial at frequencies with fairly short wavelengths of the order of $\lambda/10$ [7] can contribute to improving the electrical qualities of the filter. Most of the results obtained in modern research confirm the importance of metamaterials. Two complementary metamaterial resonators of circular spiral and symmetrical circular shapes are proposed in [8] to design a dual band bandpass filter in coplanar technology with a size of 16×9.3 mm². The designed filter covered the C-band with fractional bandwidths of 52.27 and 15.68%, respectively. In [9], a tapered metamaterial resonator-dual-band bandpass filter was proposed for X-band applications. The tapered resonators have contributed to create a considerable rejection band of the order of 1.03 GHz to minimize overlap and congestions.

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In this paper, we present a detailed analysis for designing a microstrip filter. The proposed filter with an overall size of 33.4 × 20.6 mm² is formed by two ordinary C-SRRs resonators and feeded by two microstrip lines of length of 37.1 mm. The designed filter showed a dual-band bandpass behavior for two bandwidths of 510 and 410 MHz centered on the resonances of 6.16 and 10.94 GHz, respectively. The electric field propagating in the filter (for both configurations) was also studied according to the obtained concentrations to discuss the effectiveness and the impact of the electromagnetic coupling between the two metamaterial resonators. We have structured this manuscript as follows. In Section 2, the electromagnetic behavior of the C-SRR is analyzed based on its frequency response and its refractive index. In Section 3, the simulation results are discussed. In Section 4, conclusions are drawn.

2. FILTER DESIGN

2.1 2.1 C-SRR Resonator

The resonators constituting the filter have a C-shaped patch; this later is printed on a Rogers RO 4003 substrate of thickness $h = 1.5$ mm. the C-SRR is a periodic structure with a single gap and has a period P = 8.8 mm as shown in Fig. 1.

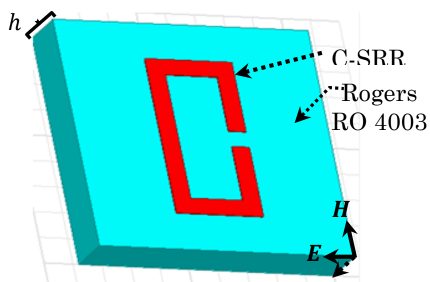


Fig. 1 – Perspective view of the proposed C-SRR.

2.2 Configurations of the microstrip filter

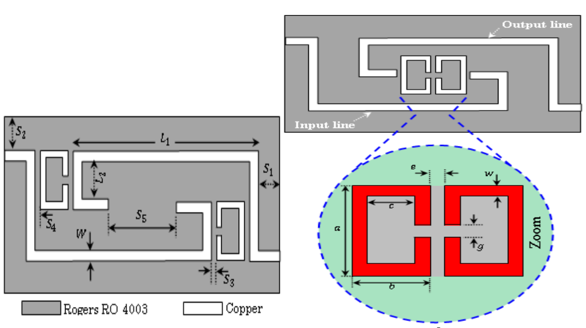


Fig. 2 – Proposed filter for: (a) First configuration, (b) Second configuration with zoom on C-SRR patch

The proposed filter is formed by two C-SRR resonators coupled to the microstrip feed lines. The design of the filter was based on two different configurations depending on the positions of the C-SRRs with respect to the feed lines. The two configurations proposed for the design of the filter are represented by Fig. 2.

Table 1 – Various parameters of the proposed filter

Parameter	Value (mm)	Parameter	Value (mm)
a	6	L_2	3.2
b	3	S_1	4
c	1.8	S_2	5
e	0.6	S_3	1
w	0.6	S_4	1
L_1	17.2	S_5	7.8
W	1.4	g	0.6

With the dimensions of the parameters listed in Table 1, the filter has the length and the width, $X = 33.4$ mm, $Y = 20.6$ mm, respectively.

3. RESULTS AND DISCUSSION

3.1 C-SRR Electromagnetic Behavior

To obtain the reflection and transmission of the C-SRR element, boundary conditions have been applied. The proposed resonator has two accesses; on each one, we have generated an electromagnetic wave to have the behavior of a transmitter and receiver ports. The frequency response of the C-SRR is shown in Fig. 3.

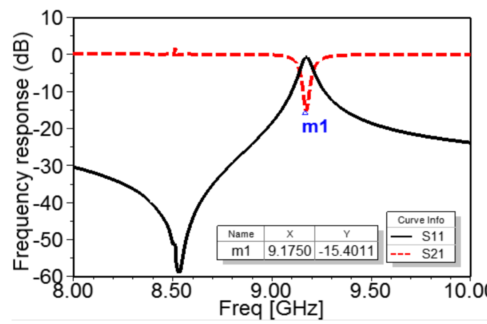


Fig. 3 – Frequency response of the C-SRR

As shown in Fig. 3, the frequency response of the C-SRR resonator represents a band-stop characteristic. The C-SRR resonates at the frequency of 9.17 GHz with a reflection of – 15.4 dB. A zero transmission appeared at the frequency of 8.53 GHz.

To explain the properties of this resonator, the analysis of these parameters is highly requested. The Nicolson-Ross-Weir (NRW) method [10, 11] is very popular to extract the effective parameters of the C-SRR. The refractive index of the C-SRR is given by the following expressions [12].

$$n_{eff} = \frac{c}{j\pi f h} \times \sqrt{\left[\frac{1-(S_{21}+S_{11})}{1+(S_{21}+S_{11})}\right]\left[\frac{1-(S_{21}-S_{11})}{1+(S_{21}-S_{11})}\right]} \quad (1)$$

There in, $c = 3 \times 10 + 8$ (m/s) is the velocity of light and h is thickness of the substrate. The real and imaginary parts of the refractive index are shown in Fig. 4.

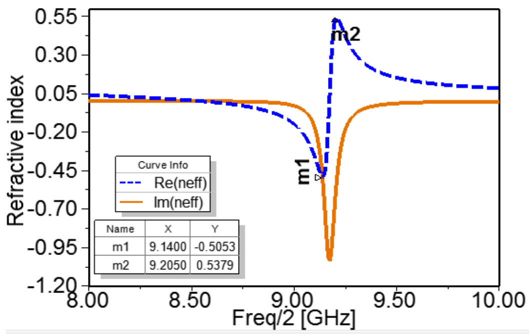
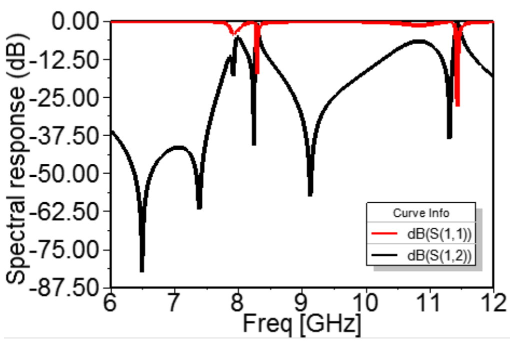


Fig. 4 – Extracted real parts of the effective permittivity and permeability of the F-SRR

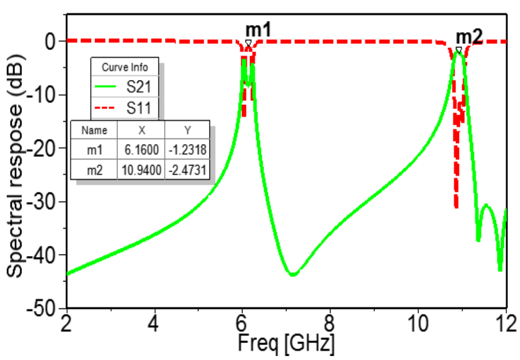
From the imaginary and the real parts of the refractive index, we can say that the C-SRR has negative values (at the same time) in the frequency range around the resonance of 9.17 GHz. This characteristic can justify the left-handed (LH) electromagnetic behavior of our metamaterial resonator.

3.2 Spectral Response of the Proposed Filter

The filter feeding for its two ports makes it possible to obtain the spectral response for each proposed configuration. This response is shown in Fig. 5.



a



b

Fig. 5 – Spectral response of the proposed filter for: (a) First configuration, (b) Second configuration

The spectral response of the filter for the two proposed configurations is shown in Fig. 5. For the case of Fig. 5 a, where the two C-SRRs are far from each other (corresponds to the first configuration), we notice that the reflection and transmission of the filter are not clear. On the other hand, the filter for this configuration has poor adaptation to both resonances. This feature is due to the level of the coupling which was not sufficient to transform the electromagnetic energy from one resonator to another. Contrary to this, we observe in Fig. 5b a clear frequency response. The behavior of the filter is dual-band bandpass for two bandwidths centered on the two frequencies of 6.16 and 10.94 GHz, respectively. The good electrical qualities of the filter for the second configuration proposed are justified by the insertion losses (IL) which are of the order of – 1.23 and – 2.47 dB at the two resonances, respectively. A single frequency of zero transmission of about –43.53 dB has been observed at 7.19 GHz can also justify the good performance of our filter.

Applying the Bloch-Floquet theorem [13], the dispersion diagram of the filter can be obtained as.

$$\beta(\omega) = \frac{1}{d} cos^{-1}(\frac{A+D}{2}) \tag{2}$$

Where d is the length of the equivalent electrical circuit (transmission line model) of the proposed filter.

And

$$\begin{cases} A = \frac{(1+S_{11})(1-S_{22})+S_{12}S_{21}}{2S_{21}} \\ D = \frac{(1-S_{11})(1+S_{22})+S_{12}S_{21}}{2S_{21}} \end{cases} \tag{3}$$

So, the dispersion is expressed as a function of the reflection (S_{11}) and the transmission (S_{21}) of the filter by the following relation.

$$\beta d = cos^{-1}\left(\frac{1-S_{11}S_{22}+S_{12}S_{21}}{2S_{21}}\right) \tag{4}$$

The dispersion diagram of the proposed filter is shown in Fig. 6.

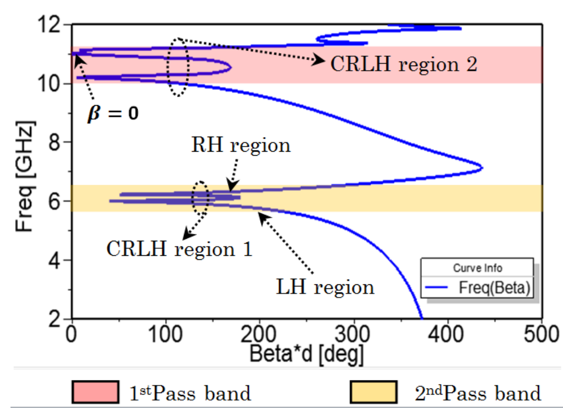
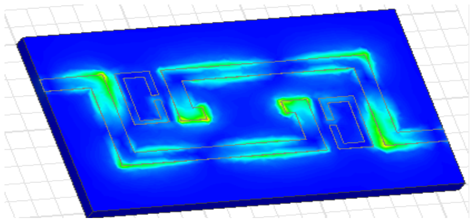


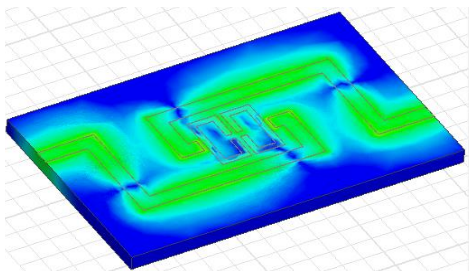
Fig. 6 – Dispersion diagram for the proposed DBBPF

From Fig. 6, we have two pass bands for the filter have been observed. For the first band (6.02 to 6.25 GHz), we notice that the dispersion characteristic has both a negative slope ($\beta < 0$) and another which is positive

($\beta > 0$), which makes it possible to define the first region composite right hand/left hand ($CRLH_1$). For the second band (10.22 to 11.13 GHz), the same feature is observed which can define the second region $CRLH_2$. The positive slopes of the phase constant in the two passbands of the filter justify once again the retro-propagation of the electromagnetic wave in the filter.



a



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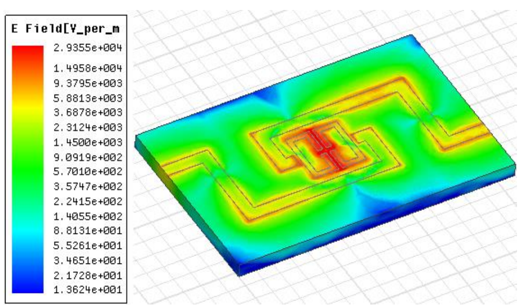

c

Fig. 7 – E-field Distribution: (a) First configuration, (b) Second configuration at 6.16 GHz, (c) Second configuration at 10.94 GHz

The distribution of the electric field on the C-SRRs and the power lines can explain the filtering mechanism. This distribution is represented for the two resonances of the filter.

In Fig. 7 a. the electric field distribution is shown for the first configuration. A slight distribution of the electric field is observed on the two feed lines and on the two metamaterial resonators. This feature can justify the poor adaptation and the low level of coupling due to this configuration (where the C-SRRs are distant from each other). For the second configuration shown in Fig. 7 b, at the first resonance of 6.16 GHz, the E-field is concentrated in all filter elements with weak values. In Fig. 7 c, for the second resonance of 10.94 GHz, the transfer of electromagnetic energy [14] (in the sense of density which is defined from the Poynting instantaneous vector expressed as a function of the electric and magnetic field) has been obtained. We notice that the E-field is concentrated between the two C-SRR resonators close to each other. This characteristic justifies obtaining the second resonance.

4. CONCLUSION

To summarize, a miniature microstrip filter has been designed for a novel configuration based on electromagnetic coupling between metamaterial resonators and matched feed lines. Two C-SRRs resonators with optimized size of 6×3 mm^2 are used to ensure the necessary coupling. The analysis of the proposed filter was done for two différents configurations according to the location of the two C-SRRs. In the first configuration, the resonators have been spaced apart, while for the second the two resonators are placed closer together. The simulation outcomes show that the filter designed according to the first configuration had a poor adaptation because of the insufficient electromagnetic coupling level. When the C-SRRs were brought closer, the filter has been exhibited dual-band bandpass behavior with a good adaptation and two clear bandwidths. The analysis of the filter carried out can justify the importance of our design for RF/microwave applications.

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Розробка мініатюрного двосмугового мікросмужкового фільтра на основі C-подібних метаматеріальних резонаторів для радіочастотних/мікрохвильових застосувань

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У цій статті запропоновано та досліджено двосмуговий смуговий мікросмужковий фільтр (DBBPF) для радіочастотних/мікрохвильових застосувань. Наш метод розробки фільтрів базується на двох основних концепціях; використання метаматеріальних резонаторів у C-подібних роз'ємних кільцях (C-SRR) для лівосторонньої поведінки (LH) з мінімізованими втратами та подачі мікросмужкової лінії значної довжини, складеної для бажаної мініатюризації. Два C-SRR оптимізовані для розміру 6×3 мм² для покриття бажаних діапазонів частот, а дві лінії живлення мають довжину 37,1 мм для забезпечення необхідної адаптації. Пошук сильного електромагнітного зв'язку між двома C-SRR і лініями живлення дозволив нам вибрати найкраще положення для розміщення наших резонаторів у фільтрі. Моделювання параметрів фільтра для двох різних запропонованих конфігурацій демонструє дві різні якості. Відповідно до результатів моделювання для двох запропонованих конфігурацій фільтра було отримано два типи частотної характеристики з різними характеристиками. Для першої конфігурації, де два C-SRR розділені складеними плечима двох ліній живлення, відповідь фільтра нечітка. На відміну від цього, частотна характеристика фільтра бажана для другої конфігурації. Запропонований фільтр, який представлено другою конфігурацією, охоплює обидва діапазони (від 5,88 до 6,39 ГГц і від 10,75 до 11,16 ГГц) для смугової поведінки. Крім того, аналіз дисперсійної діаграми дозволив нам вибрати електромагнітну поведінку, пов'язану з кожною смугою.

Ключові слова: Смуговий фільтр, Діаграма дисперсії, F-CSRR, Метаматеріал, Мікрохвильові частоти.