JOURNAL OF NANO- AND ELECTRONIC PHYSICS
Vol. **11** No 6, 06019(6pp) (2019)

ЖУРНАЛ НАНО- ТА ЕЛЕКТРОННОЇ ФІЗИКИ
Том **11** № 6, 06019(6cc) (2019)

Conceive a Filter by Engraving S Resonators to the Substrate Integrated Waveguide

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(Received 28 July 2019; revised manuscript received 05 December 2019; published online 25 December 2019)

In this paper, a bandpass filter in the hyperfrequency has been proposed by combining two planar technologies. The first is the substrate integrated waveguide (SIW) and the second is the metamaterials. For the latter, there are several forms, but in this work, we are interested in the S-shaped resonator.

A study is done to extract the equivalent circuit of different numbers of resonators add, which means different orders of the filters. The structures designed are simulated in various programs such as ADS, HFSS and CST for the validation of the results, which are perfect for the two selected frequency bands [8.7, 13.4] GHz and [9.5, 15] GHz.

Keywords: Metamaterial, Substrate integrated waveguide, Band pass filter, S resonator, HFSS, CST, ADS.

DOI: 10.21272/jnep.11(6).06019 PACS numbers: 84.40.Dc, 84.30.Vn, 84.40.Az

1. INTRODUCTION

The substrate integrated waveguide (SIW) is a transmission line used in microwave applications. As we know, the volume technology like the waveguides has several constraints, including its size, the integration with other components and the cost of its manufacture [1].

For this, the scientists have opted for the planar technology, which meets these constraints, they replace the air with a substrate of permittivity ε_r (which is a dielectric material) [2].

Many devices have been fabricated based on these techniques, like couplers, power dividers circulators and filters [3].

The filters make it possible to select the desired frequencies, to let them pass and reject the remains [4]. To add the filtering function to the SIW structure, several methods are used such as the removal of metal pieces from the upper metal plate; this operation is called defective soil structures (DGS) [5]. If the refractive index n of these structures is negative, then they are materials of left hand or metamaterial [6].

The term metamaterial refers to an artificial composite material that has electromagnetic properties that are not found in a natural material [7].

There are several known forms of metamaterial as Fig. 2 shows.

In this article, we present a bandpass filter by implement S-shape to SIW structure.

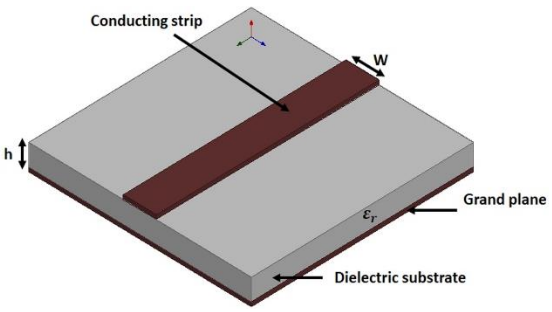
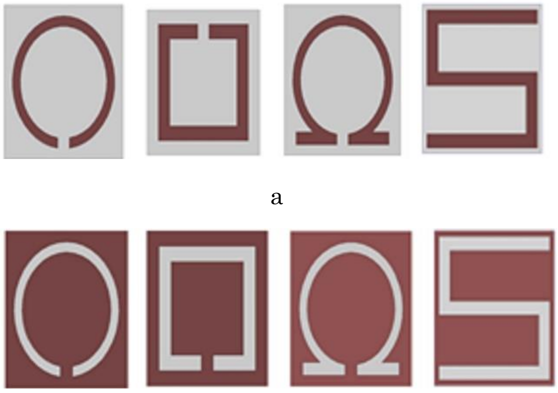


Fig. 1 – General microstrip structure



a

b

Fig. 2 – Split ring resonator (SRR) (a), complementary split ring resonator (CSRR) (b)

2. METHOD

2.1 The Substrate Integrated Waveguide

SIW is a transmission line composed of two metal plates, in the middle of them there is a substrate of permittivity ε_r.

On both sides, there are two rows of via (which make the difference between SIW structure and microstrip line). These via guide the wave inside the structure and do not let it out.

$$w_{siw} = \frac{c}{2\, f_c \sqrt{\varepsilon_r}} - \frac{d^2}{0.95\, p}\,, \qquad (1)$$

where f_c is the cutoff frequency, c is the speed of light in air, d is the diameter of the via and p is the distance between two consecutive vias [1].

To adapt the impedance of SIW to that of the power line, a structure called taper has been used, which has several forms, including a cone [8].

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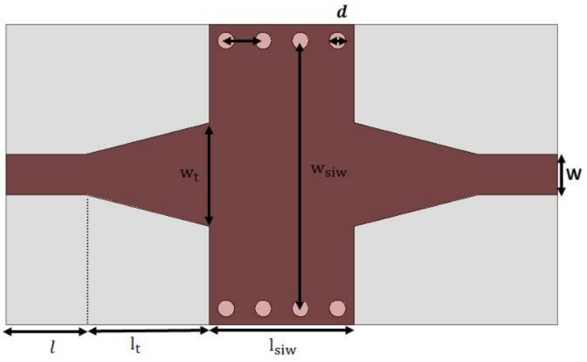


Fig. 3 – Schematic of the SIW structure

2.2 Metamaterial

The term metamaterial refers to an artificial composite material; it has electromagnetic properties that do not exist in a natural material [7].

In the domain of material physics and in particular in electromagnetism, a homogeneous material such as the dielectric or the conductor, can be characterized by its constituent intrinsic parameters which are the permittivity (ε) and the permeability (μ), whereas for non-homogeneous materials such as metamaterials, they can be characterized by parameters called "effective", which corresponds to an equivalent material [3]

$$n_{eff} = \sqrt{\varepsilon_{eff}\ \mu_{eff}}\ , \tag{2}$$

where ε_{eff} is the effective permittivity and μ_{eff} is the effective permeability.

Among the properties of metamaterials, a negative refractive index which is required magnetic permeability and, simultaneously, a negative electrical permittivity.

That means the trihedron formed by the vectors k, E, H is inverted.

There are different types of metamaterials, but they are usually composed of two parts: the substrate and the resonators. The substrate corresponds to the base of the metamaterial on which the resonators are placed. These can be of different size and geometry depending on the type of wave studied [6].

2.3 The S Resonator

Our objective in this work is to design a Chebyshev band pass filter by implement complementary S resonator to SIW structure.

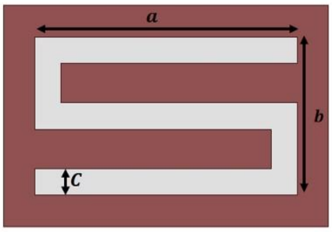


Fig. 4 – Different dimensions of S metamaterial form

To determine the equivalent circuit of an SRR structure, it is necessary to consider a series capacitance for each interval in the metal (whatever the position of the interval). So, if we have two holes, two serial abilities must be considered. In addition, the inductance occurring due to the loops must also be taken into account with a series inductor in the equivalent circuit model [9].

For the case of a CSRR structure, the same behavior is observed due to the duality theory. Therefore, the procedure for obtaining the equivalent circuit model is the same, but with a capacitance instead of inductance, and an inductance instead of a capacitance in series for each gap in the metal. Examples and different configurations of this technique can be seen in [10].

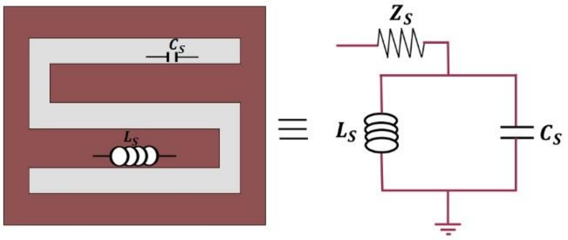


Fig. 5 – The equivalent circuit of the S resonator

Note that, regardless of the configuration and the equivalent model obtained, it is always possible to reduce it to an LC circuit in series or in parallel, like any microstrip line

$$L_{eq} = \frac{Z\ FBW}{2\,\pi\ f_0\ g_i\ g_{i+1}} \times 10^9 (nH)\ , \tag{3}$$

$$C_{eq} = \frac{g_i\ g_{i+1}}{2\,\pi\ f_0\ Z\ \ - FBW} \times 10^{12}\ (pF)\ , \tag{4}$$

$$Z_{eq} = \frac{Z}{\sqrt{g_i\ g_{i+1}}}\ . \tag{5}$$

BW is the band width ($BW = f_2 - f_1$) and FBW is the relative band width ($FBW = (f_2 - f_1)/f_0$)), where f_1, f_2, f_0 are respectively the lower cut-off frequency, the higher cut-off frequency, the center frequency; g_i are the element values for Chebyshev low pass prototype filters, Z is the impedance of the power line of 50 Ω and n is the number of resonators [3, 4].

3. FILTER DESIGN

In this article, we design two band pass filters of two different orders 2 and 3 by adding different number of the S metamaterial chaps to the SIW.

3.1 The Filter of Order 2

Before treating the combination of SIW and metamaterials, we study each structure alone to know its response and its properties.

We started with designing SIW structure in the band [8.7, 13.4] GHz. The substrate used is Roger Duroid 5880 of $h_{siw} = 0.787$ mm, $\varepsilon_r = 2.2$ and $\tan\delta = 0.0009$, which are respectively its height, permittivity and loss tangent. This substrate has the lowest loss tangent of all PTFE materials (Polytetrafluoroethylene) and this makes it well adapted for high frequency broadband applications.

Knowing that, it is easy to cut it and shape it, because it resists to all solvents and reagents used in the etching of the printed circuit.

Using the equation (1), we calculated the initial dimensions, which allowed us to draw 3D structure in the HFSS (High Frequency Structure Simulator) program. They are optimized for good transmission. The final sizes are in Table 1.

The response shows that the reflection is less than – 15 dB in the desired band.

Now, we pass to simulate the complementary S resonator.

The size in Table 2 was used to conceive our structure in HFSS, and its responses allow us to extract the different electromagnetic parameters of this structure (the effective permittivity ε_{eff}, the effective permeability μ_{eff} and the effective refraction index).

Before designing our filter, we must first elaborate its different properties that are called filter specification.

In this application, we have opted for this specification. The filter type is Chebyshev, the center frequency is $f_0 = 10.4$ GHz with *BW* of 1.57 GHz and *FBW* = 15.09 %, the number of resonators is $n = 2$ and finally the g values are $g_i = [1 \quad 1.0379 \quad 0.6746 \quad 1.5386]$.

The equations (3)-(5) allow us to calculate the various parameters of the equivalent circuit.

Table 1 – The dimension of SIW in [8.7, 13.4] GHz

w_s	w_t	w	l_t	l	d	p
12.9243	3.2	1.9541	5	$w \times 2$	0.8	1.8

Table 2 – The dimension of S resonator

a	b	c
5 mm	3 mm	0.5 mm

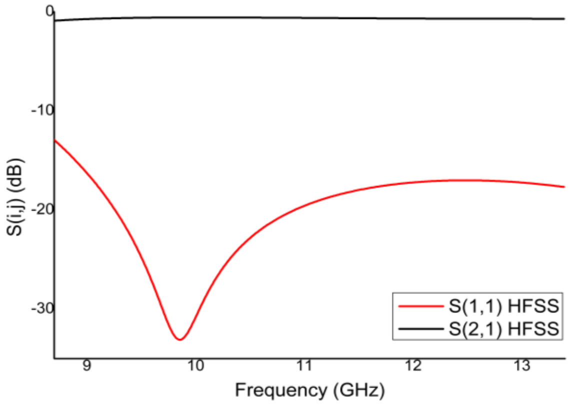
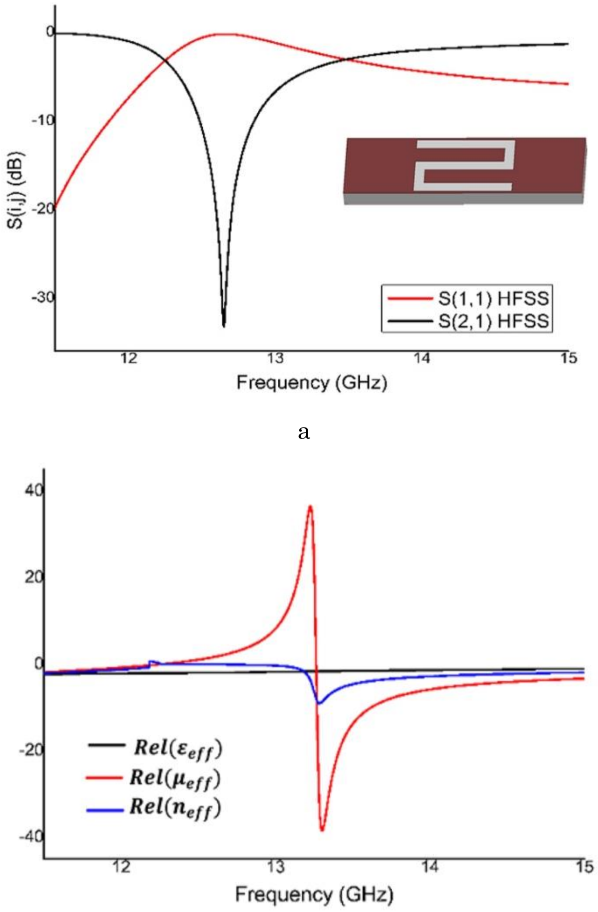


Fig. 6 – The response of SIW structure in [8.7, 13.4] GHz band

The circuit is conceived in ADS (Advanced Design System v2016.01) (see Fig. 8).

Now, we insert two S resonators to the SIW structure. Due to this change in the SIW, its interior impedance change too, that means the dimension of the transition change.

Fig. 9b shows the frequency response of the circuit in ADS and the SIW structure, which is simulated with two programs HFSS and CST (Microwave Studio Software v2014.00) to validate the results.



a

b

Fig. 7 – The frequency response (a), permittivity, permeability and the refractive index of complementary S resonator (b)

Table 3 – Parameters of the electrical circuit

l_{eq}	C_{eq}	Z_1	Z_2
0.1113 nH	2.1042 pF	49.0793 Ω	40.3096 Ω

Table 4 – 2nd order filter dimensions

w_t	l_t	x_1	x_2	l_1	l_2
2.9983	5.9966	4.6	0.6	0.8	0.3

3.2 The Filter of Order 3

Now we will choose another filter in another frequency range (see Fig. 11, Fig. 12, Fig. 13). The same steps used to design the previous filter are as follows.

That means, we started by designing SIW structure in the novel band [9.5, 15] GHz by using the same substrate Roger Duroid 5880.

The new dimensions are in Table 5.

This structure is simulated in HFSS.

The S_{11} parameter is less than – 16 dB in the desired band.

We will pass to design our filter, for that we select new specifications.

– Filter type: Chebyshev.
– The center frequency $f_0 = 11.85$ GHz.
– The band width $BW = 2.2$ GHz.
– The relative band width $FBW = 18.56$ %.

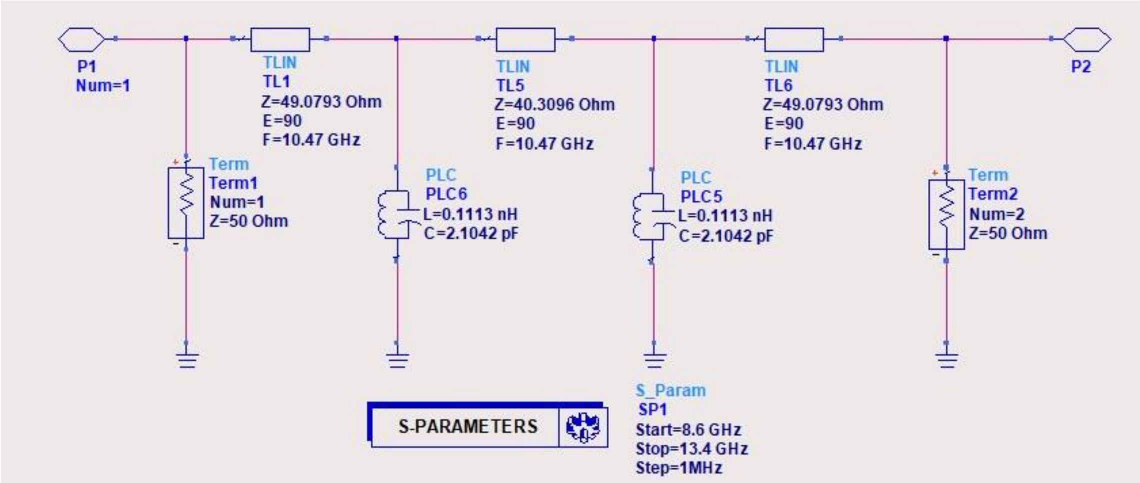
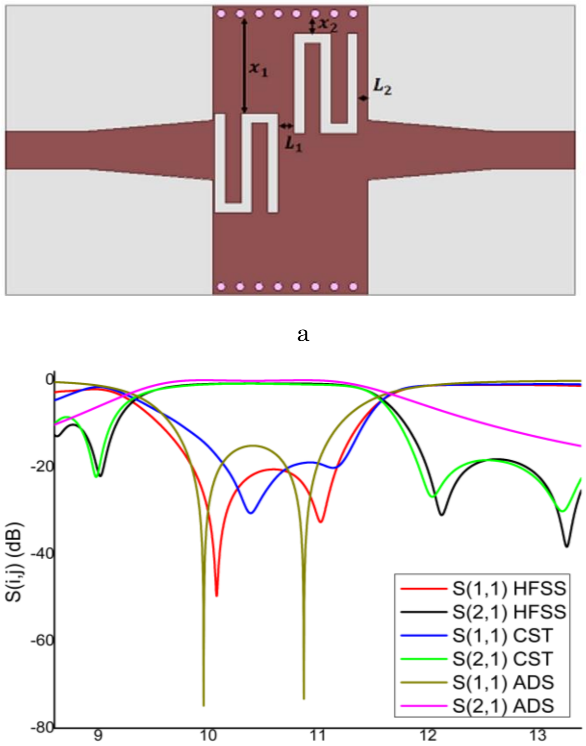


Fig. 8 – The bandpass electrical circuit with ADS



a

b

Fig. 9 – SIW structure + two S resonators (a), the frequency response (b)

– The number of resonators $n = 3$.

– The g values $g_i = [1 \quad 1.006 \quad 1.1438 \quad 1.006 \quad 1]$.

This specification allows us to calculate the equivalent circuit.

Table 5 – The dimensions of SIW in [9.5, 15] GHz

w_s	w	w_t	l_t	l	d	p
12.9243	1.9541	3.5	5	w*2	0.7	1.4

We insert three S resonators to the SIW structure.

The arrangement of S in the structure is shown in Fig. 13a.

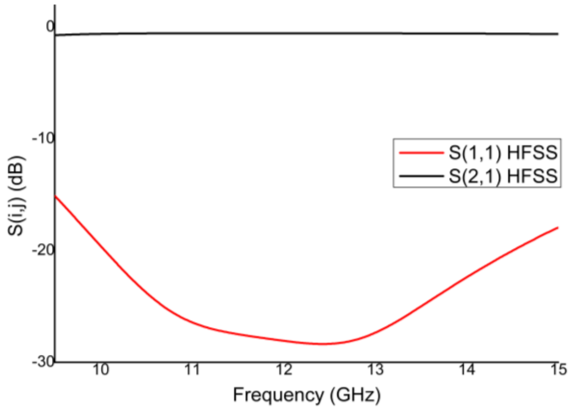


Fig. 10 – The response of SIW structure in [10.1, 15] GHz band

Table 6 – Parameters of the electrical circuit

l_{eq}	C_{eq}	Z_1	Z_2
0.1304 nH	1.4556 pF	49.8495 Ω	53.3138 Ω

Table 7 – 3rd order filter dimensions in millimeter

w_t	l_t	a	b	c
2.9983	5.9966	4.8	2.5	0.5
x_1	x_2	l_1	l_2	l_3
0.35	1.65	0.4	0.4	1.1

By using these sizes, we observe that our requirement is not respected, and that the reflection is under – 13 dB.

As a solution, we duplicate the shape of three resonators with a distance between them of $x_3 = 0.6$ mm.

4. DISCUSSION OF RESULTS

In this research, we focused on designing a bandpass filter with planar technology by using the SIW and the metamaterial in order to benefit advantages of each one of them.

Among the existing forms of metamaterials, the form S was selected and tested.

First, we study each structure alone. The SIW operates as a simple transmission line, the signal enters

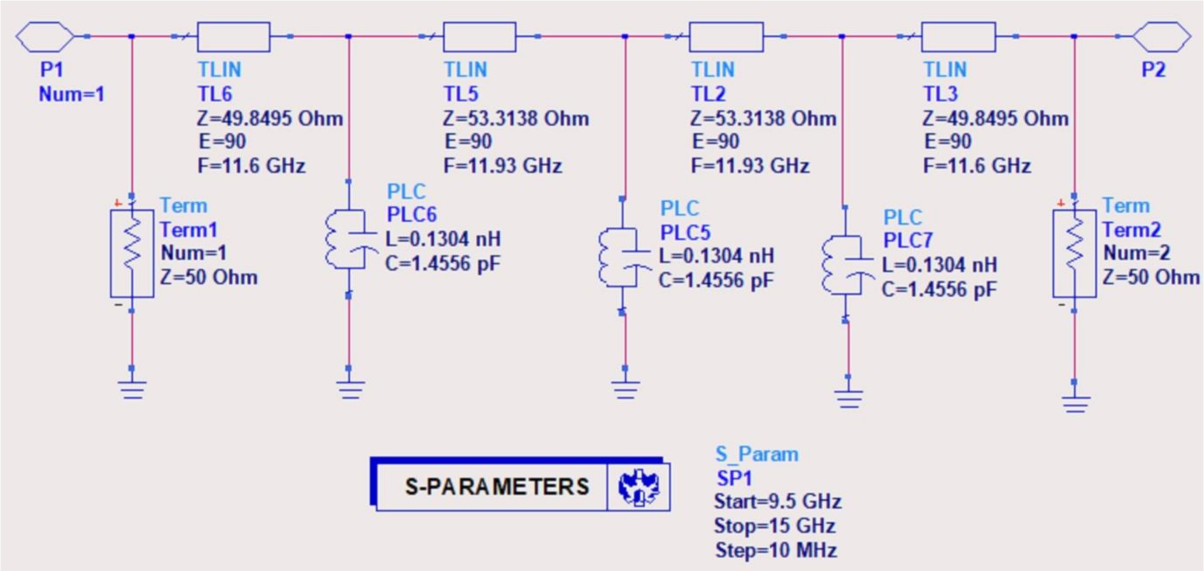
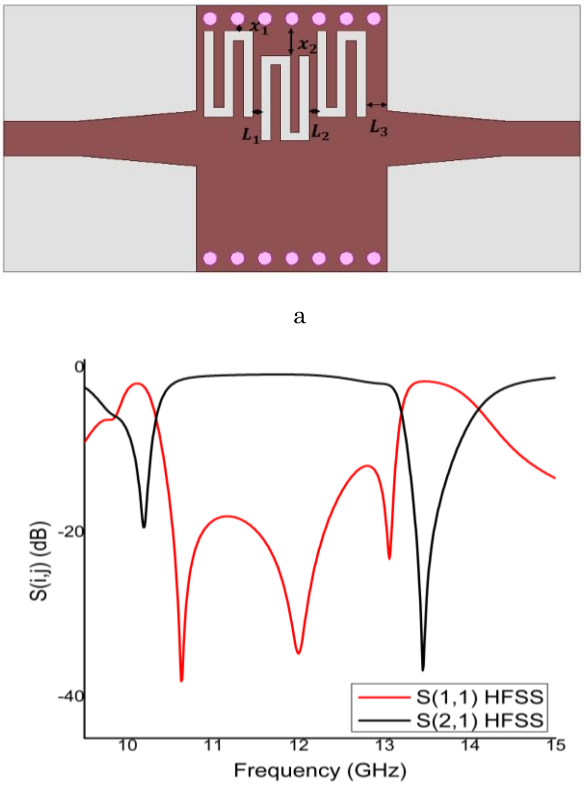


Fig. 11 – The bandpass electrical circuit with ADS



a

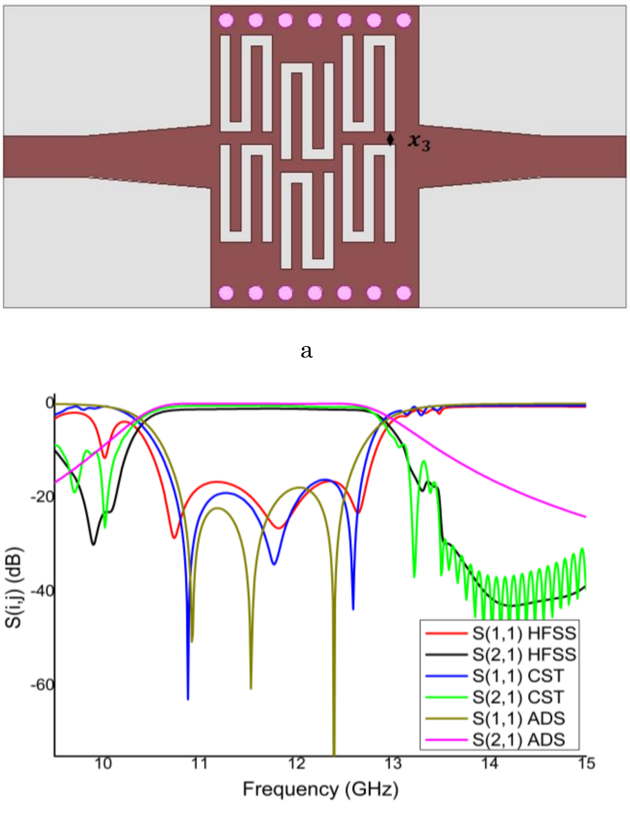
b

Fig. 12 – SIW structure + three S resonators (a), the frequency response (b)

through port 1 and exits port 2 without visible influential loss, with a reflection coefficient less than – 15 for the two selected bands.

In the second step, we design the S metamaterial in HFSS; the S_{ij} parameter of the CSRR (Fig. 7a) resonates at 12.7 GHz with a return loss equal to – 34 dB.

In Fig. 7b we clearly see when both the permittivity and permeability are negative, the refraction index is negative.



a

b

Fig. 13 – SIW structure + six S resonators (a), the frequency response (b)

After these studies, we combine two S resonators with the SIW structure. A Chebyshev bandpass filter of order 2 is obtained. The results are very good. Our specifications are respected in terms of the center frequency, the bandwidth and the number of the ripples (one ripple that means two peaks corresponding to the order 2 (two resonators)), and the reflection levels is less than – 19 dB.

Thereafter, we add three S resonators, the answers obtained are not satisfactory (the reflection is around – 13). As a solution, the three resonators are duplicated.

Table 8 – The parameters of the two simulations

	1st simulation	2nd simulation
Band width	1.75 GHz	2.2 GHz
Length of SIW	27 mm	29.4 mm
Width of SIW	14.5 mm	14.3 mm
The reflection	– 19 dB	– 19.1 dB

The desired results have been achieved, and our specifications are respected. A good compatibility is seen between the responses, for both the electric circuit ADS and that of the simulated structure in the two programs HFSS and CST.

The S forms burner at the SIW allowed us to widen the bandwidth and therefore enlarge the relative bandwidth ($FBW_1 = 15.09$ % and $FBW_1 = 18.56$ %) and design broadband filters with perfect responses.

5. CONCLUSIONS

In the microwave field, there are many methods to design a bandpass filter. In this article, we are interested in the combination between the waveguide integrated in the substrate and the metamaterials, in particular the S-shaped resonators.

This combination allows us to obtain a filter with a considerable bandwidth, which makes it easy to manufacture it and to integrate it.

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Створення фільтру за допомогою гравірування S-резонаторів до хвилеводу, інтегрованого у підкладку

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У роботі запропоновано смуговий фільтр у гіперчастотному діапазоні за рахунок поєднання двох планарних технологій. Перша технологія – це хвилевод, інтегрований у підкладку (SIW), а друга – метаматеріали. Щодо метаматеріалів, існує декілька їх форм, але в роботі нас цікавить S-подібний резонатор. Дослідження проводиться для вилучення еквівалентної схеми з додаванням різного числа резонаторів, що означає різний порядок фільтрів. Створені структури моделюються в різних програмах, таких як ADS, HFSS та CST для підтвердження результатів, які ідеально підходять для двох вибраних діапазонів частот [8,7; 13,4] ГГц та [9,5; 15] ГГц.

Ключові слова: Метаматеріал, Інтегрований у підкладку хвилевод, Смуговий фільтр, S-резонатор, HFSS, CST, ADS.