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Comparison on the Substrat Integerated Wave Guide Filter Based on Complementary Split Ring Resonators (CSRRs)

Damou Mehdi[*,1], Nouri Keltouma[1], Feham Mohammed [2] and Khazini Mohammed[1]

[1]Laboratoire de Technologies de Communications TC, Faculté technologie, Université Dr Moulay Tahar, – BP 138– Ennasr, Saida, Algérie

[2]Laboratoire de recherche Systèmes et Technologies de l'Information et de la communication, STIC, Faculté de Technologie - Université de Tlemcen – BP 119 – Tlemcen, Algérie

[*]bouazzamehdi@yahoo.fr

***Abstract*— In this paper, two bandpass SIW filter based on Complementary Split Ring Resonators (CSRRs) were presented for X-band applications. Which are designed by two methods, . The bandpass filter is treated by two softwares. The first software concerns the use of CST Microwave Studio (Computer Simulation Technology) based by method of moment and three square double rings CSRRs cells are etched in the top plane of the SIW, the simulated results of this filter have shown that the passband is from 7.350 GHz to 8.850 GHz, while the insertion loss is -0.8350 dB within 18.59 % bandwidth around 8.450 GHz and input return loss in the passband is better than -14.92 dB. The second software concerns the finite element method (FEM) based on a commercial software package HFSS (High Frequency Structure Simulator) is used for simulations and three square double rings CSRRs cells are etched on the top plane of the SIW, the simulated results of this filter have shown that the passband is from 7.20 GHz to 8.750 GHz, while the insertion loss is -0.8141 dB within 19.27% bandwidth around 8.350 GHz and the return loss in the passband is better than -17.05 dB. All the structures are designed on a single substrate of RT / Duroid.**

***Index Terms*— Substrate Integrated Waveguide, Via, Microwave Filters, Transition, SIW-Microstrip Technology, Complementary Split Ring Resonators and Square**

I. INTRODUCTION

VERY recently?, Complementary split ring resonators (CSSRs) elements have been proposed for the synthesis of negative permittivity and left-handed (LH) metamaterials in planar configuration [1] (see Fig 1). As explained in [2], CSRRs are the dual counterparts of split ring resonators (SRRs), also depicted in Fig. 1, which were proposed by pendry in 1999. It has been demonstrated that CSRRs etched in the ground plane or in the conductor strip of planar transmission media (microstrip or CPW) provide a negative effective permittivity to the structure, and signal propagation is precluded (stopband behavior) in the vicinity of their resonant frequency. CSSRs have been applied to the design of compact band-pass filters with high performance and controllable characteristics [3]. Recently, a new concept "Substrate Integrated Waveguide (SIW)" has already attracted much interest in the design of microwave and millimeter-wave integrated circuits. The SIW is synthesized by placing two rows of metallic via-holes in a substrate. The field distribution in an SIW is similar to that in a conventional rectangular waveguide. Hence, it takes the advantages of low cost, high Q-factor etc., and can easily be integrated into microwave and millimeter wave integrated circuits. This technology is also feasible for waveguides in low temperature co-fired ceramic (LTCC). The SIW components such as filter, multiplexers, and power dividers have been studied by researchers [4]. In this paper, a band-pass SIW filter based on CSRRs is proposed for the first time. The filter is consisted of the input and output coupling line with the CSRRs loaded SIW. Using the high-pass characteristic of SIW and band-stop characteristic of CSSRs, a bandpass SIW filter is designed. We will do a detailed investigation of CSRRs based stop band filters: starting with a single CSRRs etching in the microstrip line, finding its stop band characteristics and quality factor. Then the effect of number of CSRRs etching and periodicity on the stop band filter performance will be investigated.

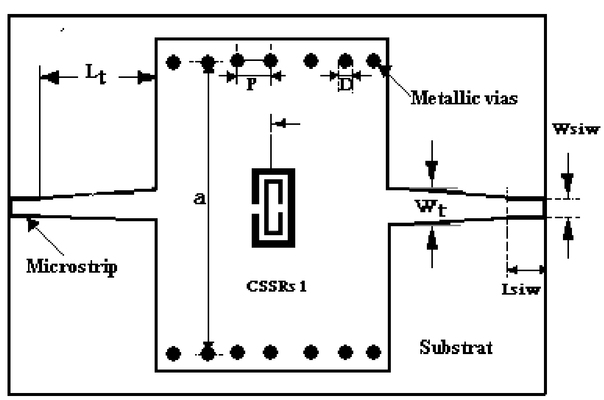


Fig. 1: Topology of the substrate Integrated Waveguide by CSRRs

II. PARAMETER DESIGN OF SIW

The SIW was constructed from top and bottom metal planes of substrate and having two arrays of via holes in the both side walls as shown in Fig. 2. Via hole must be shorted to both planes in order to provide vertical current paths, otherwise the propagation characteristics of SIW will be significantly degraded. Since the vertical metal walls are replaced by via holes, propagating modes of SIW are very close to, but not exactly the same as in rectangular waveguide [5].

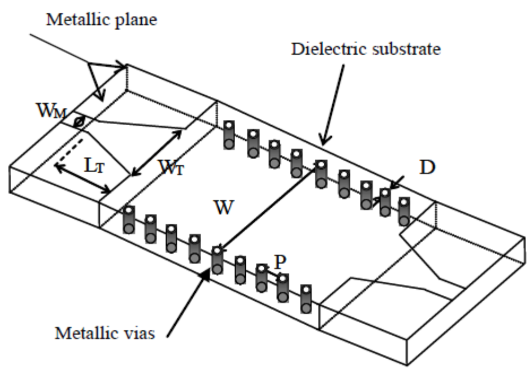


Fig. 2: Topology of the substrate Integrated Waveguide

By using equivalence resonance frequency of SIW cavity is determined from [6]:

$$f_{101} = \frac{c}{2\pi\sqrt{\mu_r \varepsilon_r}}\sqrt{\left(\frac{\pi}{w_{eff}}\right) + \left(\frac{\pi}{l_{eff}}\right)} \qquad (1)$$

This is to ensure that the SIW filter be able to support TE_{10} mode in the operating frequency range. The T*E*-field distribution in SIW is just like in the conventional rectangular waveguide. The effective or equivalent width and length of SIW cavity can be determined from:

$$w_{eff} = w - \frac{d^2}{0.95p} \qquad (2)$$

$$l_{eff} = l - \frac{d^2}{0.95p} \qquad (3)$$

Where *w* and *l* are the real width and length of SIW cavity. However *D* is the diameter and *P* is the pitch, also known as distance between center to center of adjacent via hole.
Via holes form a main part of SIW in order to realize the bilateral edge The diameter and pitch is given by:

$$d < \frac{\lambda_g}{5} \qquad (4)$$

$$p \leq 2d \qquad (5)$$

In order to minimize the leakage loss between nearby hole, pitch needs to be kept as small as possible based on (4) and (5) above. The diameter of via hole also contributes to the losses. As consequences, the ratio *d/p* reflected to become more critical than pitch size of via hole.

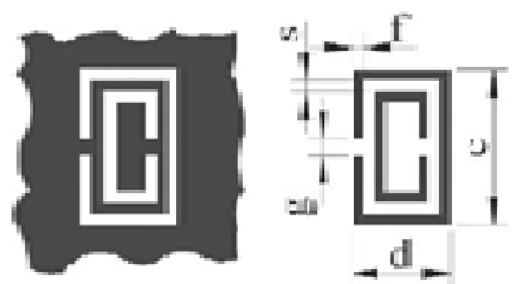
This is because the pitch and diameter are interconnected and it might distract the return loss of the waveguide section in view of its input port [7]. The SIW components can be initially designed by using the equivalent rectangular waveguide model in order to diminish design complexity.

The effective width of SIW can be defined by:

$$w_{eff} = w_{siw} - 1.08\left(\frac{D_{via}^2}{S_{vp}}\right) + 0.1\left(\frac{D_{via}^2}{w_{siw}}\right) \qquad (6)$$

A) Complementary split ring resonators "CSRRs"

The electromagnetic properties of SRRs have been already analysed in [8]. This analysis shows that SRRs behave as an LC resonator. Split Ring Resonator (SRRs) is a well known sub-wavelength metamaterial structure that exhibits negative values of permeability over a narrow frequency band around it resonance frequency. The resonant frequency is determined from the geometrical parameters of SRR. The SRR can have different types of structures (square, circular, Omega ...) with single ring, double ring or multiple ring SRR cells The Complementary Split Ring Resonator CSRRs is the complementary of SRRs [8]. The CSRR the rings are etched on a metallic surface and its electric and magnetic properties are interchanged with respect to the SRRs. Fig 3 shows the difference between the double rings SRRs and the double rings CSRRs. In fact, all the conductive part (rings) and the dielectric part of the SRRs are respectively replaced by the dielectric and conductive plan of a substrate in the CSRRs.



a b

Fig. 3: Geometry square of the double rings (a) square double rings- CSRRs (b) double rings SRRs

"d" denotes the length of the side of the square, "f" denotes the width of the conductor, "s" denotes the dielectric width between the inner and the outer square and "g" denotes the gap present in the rings. Care is taken that the gap width "g" does not change from the inner ring to the outer ring. The resonance frequency is obtained by using the equivalent circuit analysis method as prescribed in [5]. When a magnetic field is applied perpendicularly to the plane of the ring, the ring begins to conduct and gives rise in current flow. The current flowing through the rings will enable it to act as an inductor and the dielectric gap (s) between the rings will lead to mutual capacitance. Hence the equivalent circuit of the square CSRRs with double rings will be a parallel LC resonant circuit in [9]. The resonance frequency is calculated by the relation (7).

$$f = \frac{1}{2\pi\sqrt{LC}} \qquad (7)$$

The expressions for effective inductance and capacitances can be obtained from [10] as follows:
The capacitance is given by:

$$C = 4\left(\frac{\varepsilon_0}{\mu_0}\right)L_1 \qquad (8)$$

With L_1 present the inductance of the equivalent circuit proposed for square SRRs in [10].

$$L_1 = \frac{4.86\mu_0}{2}(d-f-s)\left[ln\left(\frac{0.98}{\rho}\right)+1.84\rho\right] \qquad (9)$$

Where, d, f, s are the notations prescribed in the previous section, ρ is the filling factor of the inductance and is given by

$$\rho = \frac{f+s}{d-f-s} \qquad (10)$$

The inductance is given by:

$$L = \left(\frac{\mu_0}{4\varepsilon_0}\right)C_1 \qquad (11)$$

With C_1 present the capacitance of the equivalent circuit proposed for square SRR in [10].

$$C_1 = \left(d - \frac{3}{2}(f+s)\right) \qquad (12)$$

Where, C_{pul} is the per-unit-length capacitance between the rings which is given as below

$$C_{pul} = \varepsilon_0\varepsilon_{eff}\frac{K\left(\sqrt{1-k^2}\right)}{K(k)} \qquad (13)$$

Here, ε_{eff} is the effective dielectric constant which is expressed as

$$\varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} \qquad (14)$$

K (k) denotes the complete elliptical integral of the first kind

$$K(k) = \frac{\pi}{2}\sum\left[\frac{(2n)!}{2^{2n}(n!)^2}\right]^2 \alpha^{2n} \qquad (15)$$

With k expressed as:

$$k = \frac{s}{s+2f} \qquad (16)$$

The square single ring CSRRs is shown in Fig. 3 (b), this resonance frequency is determined by the same relation the square double rings CSRRs, with the dielectric width between the inner and the outer square is null. Let us now analyze the CSSRs loaded SIW. Since CSRRs are etched in centre of the top layer, and they are mainly excited by the electric field induced by the SIW, this coupling can be modeled by connecting the SIW capacitance to the CSRRs.

According to this, the proposed lumped-element equivalent circuit for the CSRR loaded SIW is that depicted in Fig. 4. As long as the electrical size of the CSRRs is small, the structure can be described by means of lumped elements. In these models, *L* is the SIW inductance, *C* is the coupling capacitance between the SIW and the CSRR. The resonator is described by means of a parallel tank [11], *Lc* and *Cc* being the reactive elements and *R* accounting for losses.

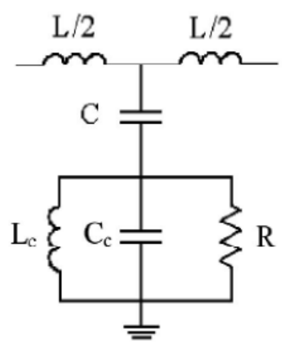


Fig. 4: The depicted equivalent circuit models

In order to demonstrate the viability of the proposed technique, we have applied it to the determination of the electrical parameters of the single cell CSSRs loaded SIW.

III. FIRST DESIGN EXEMPLE

As the first method, the resonant properties of square double ring CSRRs are carefully studied starting with a single CSRRs etching in the top plane of the SIW is shown in Fig. 5.

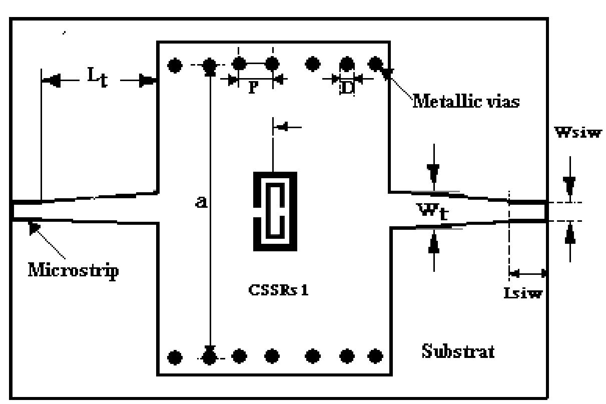


Fig. 5: Topology of the substrate Integrated Waveguide

The dimensions to the SIW are: a = 14 mm. The equivalent width of microstrip line w = 0.8 mm. The taper of microstrip line of length equal to 5.5 mrn. and SIW dimensions are a = 14mm, D = 0.8mm and P = 1.6 mm, respectively. The dimensions of the CSRR structure are c = 4mm, d = 2 mm, f = 0.3 mm, s = 0.2mm and g = 0.4mm. The width of the access lines is 0.76 mm. The simulated (using CST Microwave Studio).

A) Results and discussion by CST

The simulation results for a single CSRR etching in a microstrip line are shown in Fig. 6.

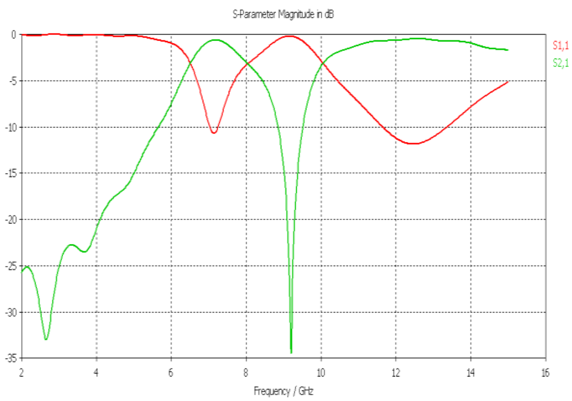


Fig. 6: Simulate frequency response corresponding to the basic cell

The results of scattering parameters versus frequency (GHz) show narrow stop band characteristics at the resonant frequency of CSRR at 9.17 GHz. By placing a single CSRR structure in the strip line, we can obtain a narrow stop band with a very low insertion loss level, which is not possible with conventional microstrip resonators. It is difficult to achieve such a good narrowband stop band response with a single element of conventional resonators. Stop bandwidth of the above single CSRRs loaded microstrip line filter is approximately 456 MHz at the resonant frequency of 9.17 GHz.

IV. DESIGN OF PROPOSED BANDPASS FILTER SIW

The proposed design of SIW bandpass filter based of three square double ring CSRRs cells is shown in Fig. 7. This structure is simulated on a the substrate used in the filter is RT/Duroid 5880 which has permittivity of 2.22, height of 0.254mm, the distance between the rows of the centres of via is w = 15 mm, the diameter of the metallic via is D = 0.8 mm and the period of the vias P = 1.6 mm. The width of tapered Wt is 1.72 mm, its length is Lt = 5.5 mm [9].

The simulated results of this filter have shown that the passband is from 7.350 GHz to 8.850 GHz, while the insertion loss is -0.8350 dB within 18.59 % bandwidth around 8.450 GHz and input return loss in the passband is better than -14.92 dB.

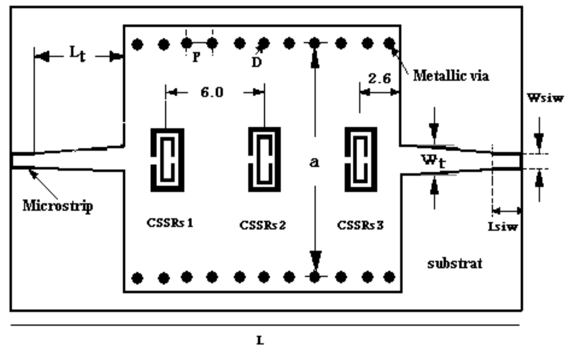


Fig. 7: Configuration for the proposed SIW Filter

TABLE 1: DIMENSIONS OF THE CSRRs STRUCTURE

CSRRs1 dimensions			
Symbol	Quality (mm)	Symbol	Quality (mm)
c	3.7	f	0.3
d	1.85	s	0.2
f	0.3	g	0.4
CSRRs2 dimensions			
Symbol	Quality (mm)	Symbol	Quality (mm)
c	4	f	0.3
d	2	s	0.2
f	0.3	g	0.4
CSRRs3 dimensions			
Symbol	Quality (mm)	Symbol	Quality (mm)
c	3.8	f	0.3
d	1.9	s	0.2
f	0.3	g	0.4
SIW dimensions			
Symbol	Quality (mm)	Symbol	Quality (mm)
Lt	5.5	Wt	1.72
W_{SIW}	0.8	L_{SIW}	1.9
D	0.8	P	1.6
A	14	L	32

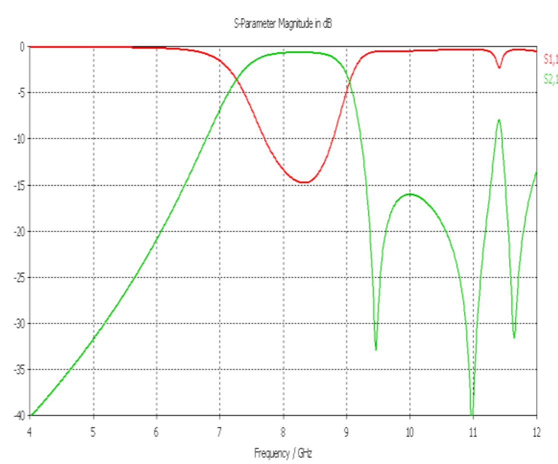


Fig. 8. Simulation results for the proposed filter SIW-CSRRs cell with CST

The optimization of the transition is performed by means of electromagnetic simulations by varying the dimensions (Lt, Wt) of the geometry. After optimization, the dimensions retained are Wt = 1.72 mm and Lt = 5.5 mm.

The distribution of the electric field is given in Fig. 9.

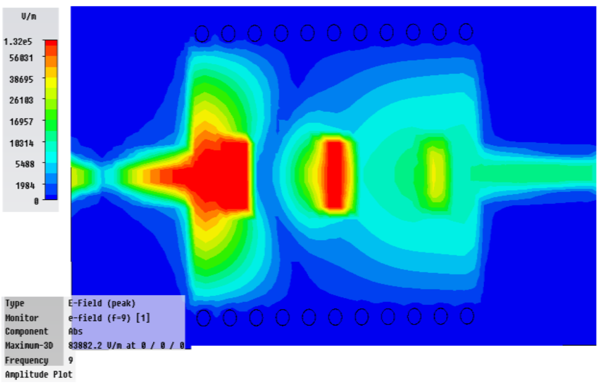


Fig. 9: Electric field distribution of proposed filter with three cascaded SIW-CSRRs cells.

A) Design of SIW filter by HFSS

The dimensions of the SIW guide with double square rings CSRR are : D = 0.8 mm, P = 1.6 mm, W_{SIW} =14 mm, W_M=0.8, d=2mm, f=0.3 mm and g=0.4 mm.

As the first method, the resonant properties of square double ring CSRR are carefully studied starting with a single CSRR etching in the top plane of the SIW is shown in Fig. 10 . The results are plotted for the scattering parameters (S_{11} and S_{12}) against frequency from 4 GHz to 12 GHz [8].

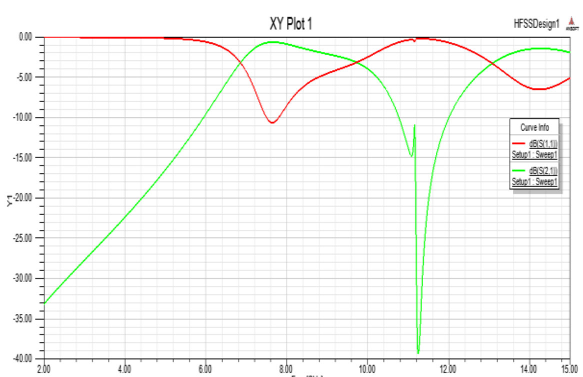


Fig. 10: Simulation results for the proposed filter SIW-CSRRs cell with HFSS

The Fig. 11 illustrated the reflection coefficient S_{11} and the transmission coefficient S_{12} of SIW bandpass filter based of three square double ring CSRRs cells and also the results in [8].

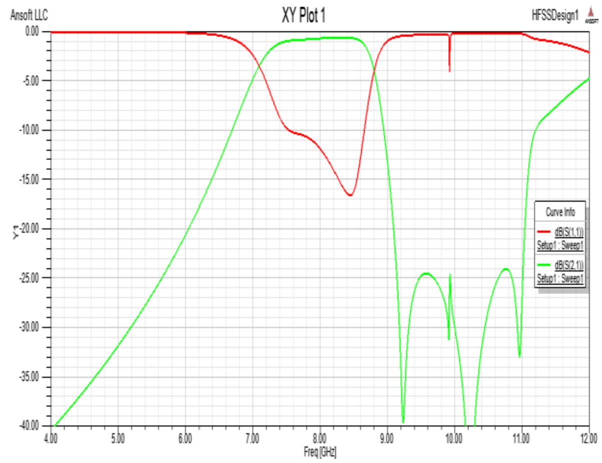


Fig. 11: Stop band filter having 3 CSSRs in the stripline Scattering parameters

From the simulated results of this filter have shown that the passband is from 7.20 GHz to 8.750 GHz, while the insertion loss is -0.8141 dB within 19.27% bandwidth around 8.350 GHz and the return loss in the passband is better than -17.05 dB.

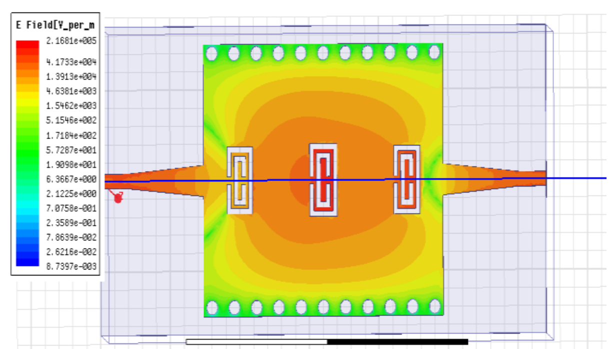


Fig. 12: Electric field distribution of proposed filter with three cascaded SIW-CSRRs cells; top layer, bottom layer

TABLE 2. FREQUENCY REPONSE FOR SIW GUIDE WIDTH DOUBLE SQUARE RINGS CSRRs WITH DIMENSIONS D = 0.8 mm, P = 1.6 mm, WSIW =16 mm, WM=0.8, WT =5.2 mm, LT =14 mm, W = 0.3 mm and G = 0.4 mm [9]

Software	Topology and Ordre	Frequency (GHz)	Attenuation (dB)	Passband frequency (GHz)	Fractional band width	Insertion loss (dB)
HFSS	SIW-CSRR Ordre 03	8.350	-17.05	7.20 to 8.75	19.27 %	-0.8141
CST	SIW-CSRR Ordre 03	8.450	-14.92	7.35 to 8.85	18.59 %	-0.8355

V. CONCLUSION

In this paper, two bandpass SIW filter based on Complementary Split Ring Resonators (CSRRs) were presented for X-band applications. Which are designed by two methods. The bandpass filter is treated by two softwares. The first software concerns the use of CST Microwave Studio (Computer Simulation Technology) based by method of moment and three square double rings CSRRs cells are etched in the top plane of the SIW, the simulated results of this filter have shown that the passband is from 7.350 GHz to 8.850 GHz, while the insertion loss is -0.8350 dB within 18.59 % bandwidth around 8.450 GHz and input return loss in the passband is better than -14.92 dB. The second software concerns the finite element method (FEM) based on a commercial software package HFSS (High Frequency Structure Simulator) is used for simulations and three square double rings CSRRs cells are etched on the top plane of the SIW, the simulated results of this filter have shown that the passband is from 7.20 GHz to 8.750 GHz, while the insertion loss is -0.8141 dB within 19.27% bandwidth around 8.350 GHz and the return loss in the passband is better than -17.05 dB. These filters are easy for integration with other planar circuit compared by using conventional waveguide. The design method is discussed; the results from our analysis are in good agreement with previous research done on this topic. These bandpass SIW filters based on Complementary Split Ring Resonators (CSRRs) are suitable for practical applications. The results obtained by CST and HFSS simulations are compared and discussed with the results in [9].

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