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Design of a Bandpass Filter with Complementary Split Ring Resonators in Evanescent-Mode

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ABSTRACT: The growing needs in the field of terrestrial and mobile telecommunications require very selective and less heavy equipment, hence the need to use very high quality Q factor filters . Also with this objective, in this article we propose to analyze the performance an inverted E-shaped Complementary Split Ring Resonator Filter (CSRRF) etched on the surface of a Substrate Integrated Waveguide (SIW). The presented filter is designed from the N + 2 transverse network coupling matrix. The design structure operates at 5 GHz, which is lower than the cut-off frequency of the waveguide which is 8.7 GHz. The proposed filter has good selectivity, low insertion loss and compact size. An excellent agreement is observed between the theoretical results, frequency responses, and group delay. The performance of the proposed bandpass filter is analyzed using HFSS.

Keywords: Complementary split-ring resonator Filter (CSRRF), rectangular waveguide, substrate integrated waveguide (SIW), transverse network coupling matrix.

I. INTRODUCTION

Split Ring Resonators (SRR), initially proposed by Pendry *et al.* [1], gained a particular interest from researchers, owing to their potential applications to the synthesis of metamaterials, which are materials with negative permeability for a particular frequency. In 2009, Yuan conducted a study on CSRR (Complementary Split Ring Resonator) filters designed on a surface of thesubstrate integrated waveguid SIW. These filtering structures permitted to highlight a bandwidth below the cut-off frequency of the waveguide [2]. In 2013, Liwen Huang designed an evanescent mode bandpass filter with complementary split-ring resonators coupled with SIW technology. This proposed filter has a compact size, high selectivity and ease of integration [3]. In 2017, Rakesh proposed a transmission line structure based on SIW loaded with an octagonal split-ring resonator (CSRR). This filter structure has two fractional bandwidths of 14.27% and 2%. The insertion losses obtained are about 0.7 dB and 2dB in the first band and the second band, respectively. A transmission zero is observed at 5.57 GHz in the attenuated band [4]. Finally, in 2017, Mostafa implemented two miniaturized planar duplexers based on SIW structure loaded with open complementary split-ring resonators (OCSRR) [5].
In this article, we propose a CSRR passband filter with evanescent-modes in SIW technology based on coupling matrix of the transverse network N + 2 method. As for conventional metallic waveguides, SIW allows filters to be developed with propagating modes or evanescent modes.

This work will be focused on the E-shaped complementary split-ring resonators in order to compare their performance with that of the square-shaped resonator filters proposed by Yuandan Dong, while the simulations will be carried out using HFSS, which is a 3D the full-wave electromagnetic simulator based on Finite Element method.

II. THEORETICAL FRAMEWORK

The evanescent-mode bandpass filter is designed to meet following specifications:

- central frequency at 5 GHz;
- fractional bandwidth of 3.2%;
- in band return lossesof 20 dB;
- transmission zero at 6.7 GHz.

This filter will now be designed using SIW technology with an inverted E-shaped complementary split-ring resonator on a Duroid/Rogers 5880 substrate with thickness h = 0.508 mm and relative permittivity ε_r = 2.2. The reference impedance is 50 Ω. The design process starts with the coupling matrix computation and ends with the determination of the structure's dimensions.
It is assumed that the filter specifications are achieved with a second-order filter. The denormalized coupling matrix [M] of the transverse network N + 2 is calculated with a computer code through MATLAB, after a rotation and is given by [6, 7] :

$$[\mathrm{M}] = \begin{bmatrix} 0 & 32.6397 & 0 & 0 \\ 32.6397 & 0.0026 & -0.0413 & -0.0021 \\ 0 & -0.0413 & -0.0032 & 32.6397 \\ 0 & -0.0021 & 32.6397 & 0 \end{bmatrix} \quad (1)$$

From the coupling matrix in equation (1), the performances of the CSRR passband filter are analyzed.

III. PERFAMANCES ANALYSIS OF CSRR FILTER

In this study, the approach presented by Yuandan Dong [2] is adopted. We choose the unit cells configuration shown in Fig. 1, where the filter consists of two pairs of face-to-face CSRRs electrically coupled or mixed and separated by a distance t.

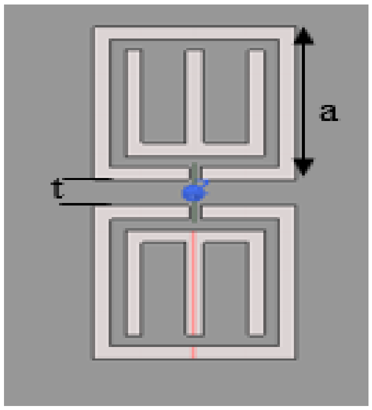

Fig. 1. Configuration of the proposed SIW-CSRR unit cell.

IV. SIW DESIGN of SIW

A. Equivalent Width

The SIW is defined by the cylindrical vias diameter d, separation P between vias, and the distance separating the two cylindrical via arrays W. A SIW is considered as a dielectric-filled rectangular waveguide which has the same cut-off frequency of the fundamental TE_{10} mode [8].

A conventional rectangular waveguide can be used to model the SIW through the so-called equivalent width W_{eff}, as shown in Fig. 2.

$$W_{eff} = \frac{c}{2 * f_C * \sqrt{\varepsilon_r}} \quad \ldots(2)$$

$$W = W_{eff} + \frac{d^2}{0.95P} \quad \ldots(3)$$

If the cut-off frequency is known, the separation between via arrays (center to center) can be calculated using equation (3), after having determined the effective width of the dielectric field waveguide from equation (2).

By considering the cut-off frequency of 8.7 GHz, the distance between the two cylindrical via arrays is found to be 12.06 mm. The other physical parameters d and P are chosen to minimize the radiation or leakage loss. And thus,all the optimized parameters of the SIW used in this study are presented in Table 1.

Table 1: Dimension of SIW.

Parameter	Description	Value (mm)
W	Vias arrays separation	11.6
d	Vias diameter	0.8
P	Pitch (separation between vias)	1.48

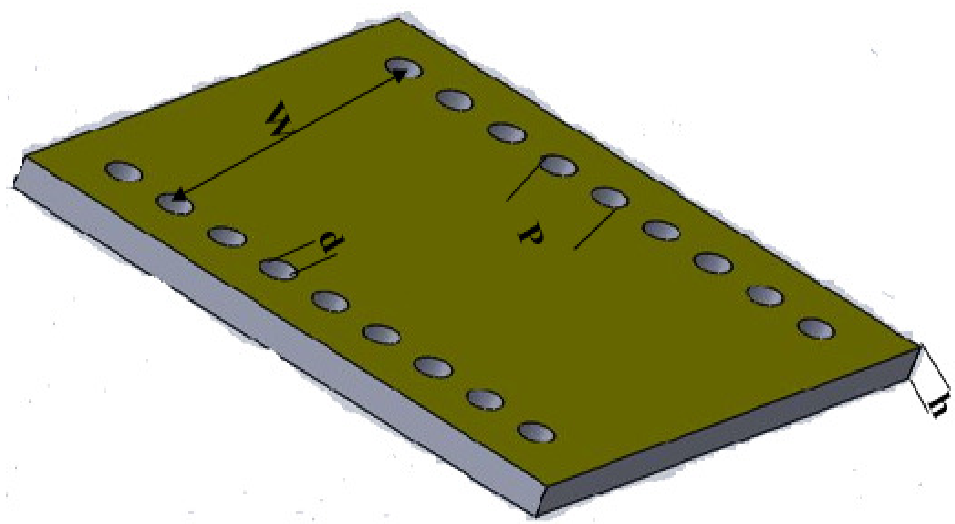

Fig. 2. Configuration of the rectangular waveguide.

B. Propagating and Diffraction Parameters of the SIW

We consider the SIW presented in Fig. 2 without CSRR cells and placed into a parallelepipedal air box having a height H as shown in Fig. 2

By performing a parametric analysis on the airbox height along with its meshing, the dispersion parameter and the frequency response of the SIW have been simulated and presented in Fig 3 and 4, respectively. The convergence of the aforementioned parameters is reached with h=10 mm, which is six times the wavelength with of 0.1 GHz.

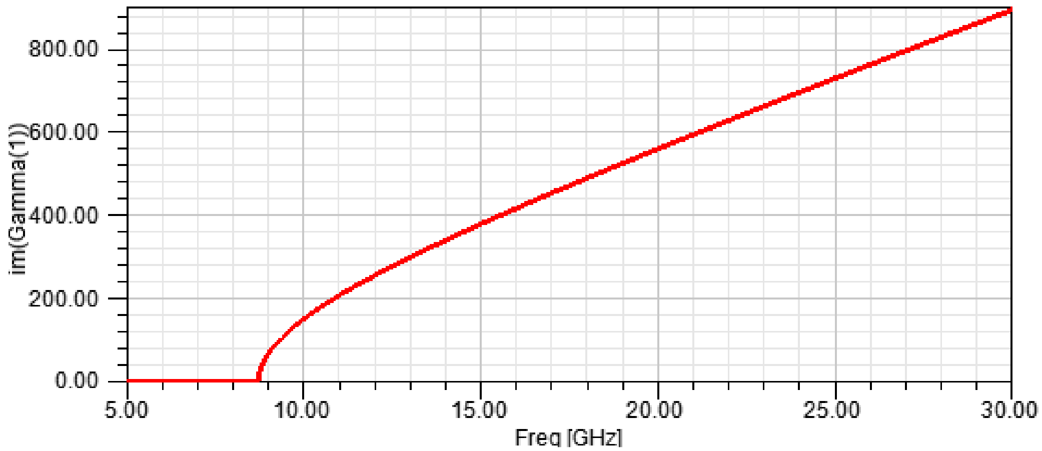

Fig. 3. Dispersion the curbe.

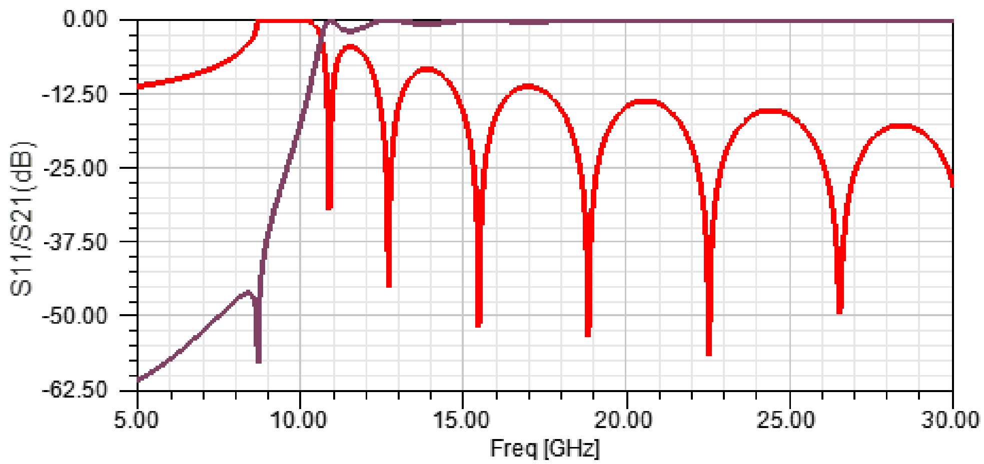

Fig. 4. Transmission(S21) and reflection coefficient (S11) for 8.7 GHz SIW structure.

As expected, we obtain a dispersion curve similar to that of a conventional rectangular waveguide with a cut-off frequency of 8.7 GHz, which is below the SIW's cut-off frequency. The modes for which the excitation frequency is less than the cut-off frequency are evanescent. It is also observed that this cut-off frequency is greater than the homogeneous rectangular guide cut-off frequency [2]. As for the frequency response curve, it shows that the SIW has a good adaptation from the cut-off frequency, as expected. Knowing the characteristics of SIW, we will discuss the design of the filter itself as a complementary E-shaped split-ring.

V. E-SHAPED CSRR BANDPASS FILTER

The SRRs of the filter have in this case the shape of an inverted E as shown in Fig. 5. To obtain the distance ld separating the two resonators that facilitates the generation of the coupling matrix given by equation (1), it is necessary to have the curve giving the coupling coefficients as a function of the distance ld which separates the two pairs of resonators. To do this, we simulated the filter transmission responses for each value of ld and then calculated by applying the following formula [9]:

$$K_c = \frac{f_2^2 - f_1^2}{f_2^2 + f_1^2} \quad (4)$$

The coupling coefficients of SRRs from these responses show two peaks for two resonant frequencies.

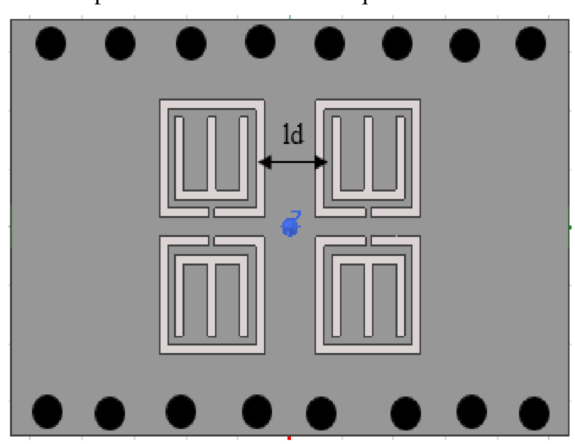

Fig. 5. Coupling between E-shaped SRR face-to-face unit cells.

The result of all the coupling coefficients obtained when varying the distance ld between resonators is given in Fig. 6.

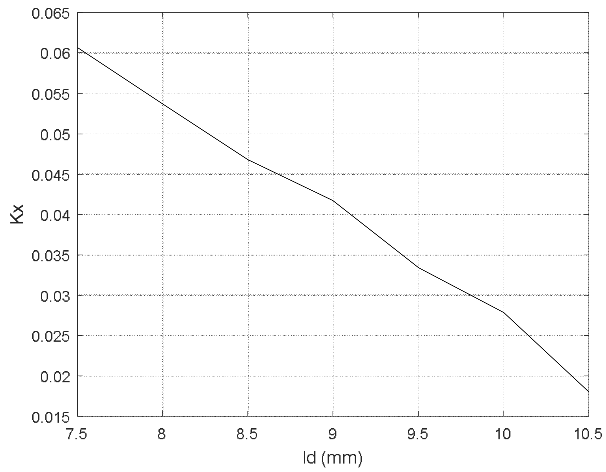

Fig. 6. Coupling between E-shaped SRR face-to-face unit cells variation versus separation between SRRs.

Two other important parameters of the filter are its input and output quality factors. They are obtained from the circuit illustrated in Fig. 7. These coefficients depend on the distance lt between the edge of the metallic patch and the SRR.

For each value of lt, the transmission response of the SRR is recorded, and the corresponding quality factors are calculated using the following formula [2].

$$Q_e = Q_s = \frac{2*f_0}{\Delta_{f-3\,dB}} \quad (5)$$

Thus, by varying the distance lt between the edge of the metallic patch and the SRR, the following quality factor plot displayed in Fig. 8 is obtained.

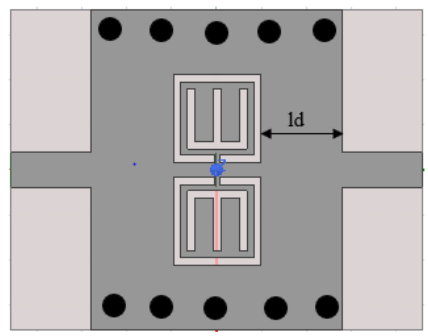

Fig. 7. Simulation diagram of the input and output quality factor.

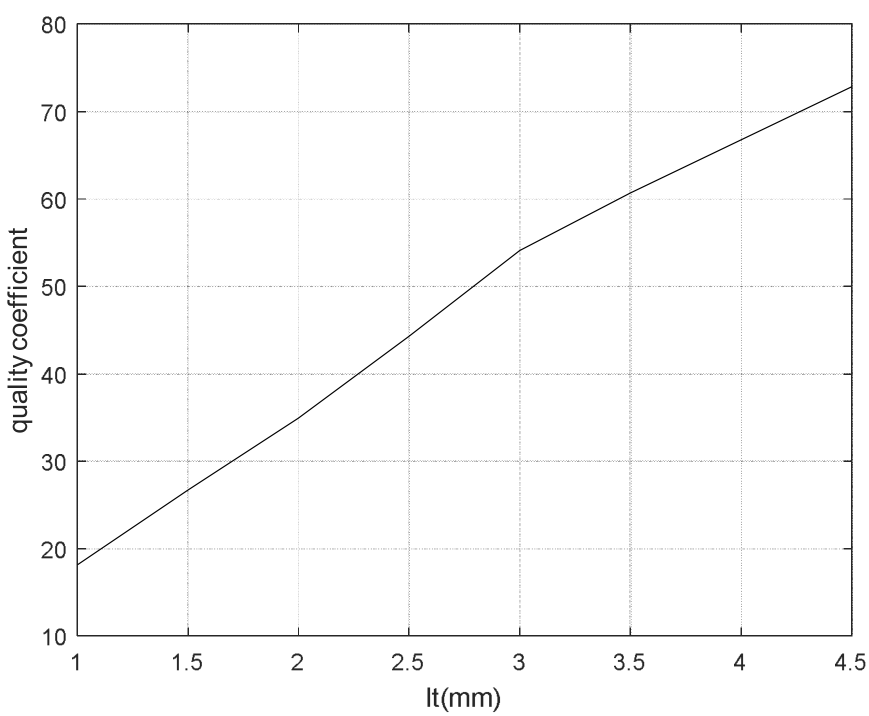

Fig. 8. Quality factor variation versus lt.

Table 2.

Designation	Parameter	Value (mm)
Resonators opening width	g	0.2
SRR length	a	4.065
Separation between two via arrays	W	12.3
Feedline width	W_1	1.53
vias diameter	d	0.8
Pitch (separation between two vias)	P	1.48
Separation between two SRR	ld	8.98
Feedline length	lt	1.82

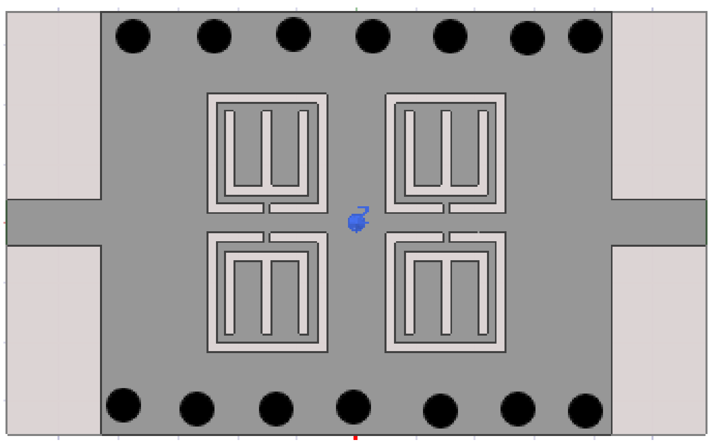

Fig. 9. Inverted E-shaped CSRR Banpass filter configuration.

Since the coupling matrix is known, all the geometric dimensions of the inverted E-shaped CSRR bandpass filter are determined from the plots results presented in Figs. 6 and 8. All the optimized filter dimensions are listed in Table 2. The geometric dimensions of the filter having been defined, the inverted E-shaped CSRR bandpass filter is modelled as shown in Fig. 9 and simulated using HFSS software. The frequency response in the frequency range [3-7] GHz is shown in Fig. 10. A center frequency of 5 GHz is obtained, as expected.

The comparison between simulated results through HFSS (curve in blue) and the theoretical response (curve in black) of the filter obtained from the coupling matrix calculated with the MATLAB software, shows an excellent agreement on the frequency range of interest.

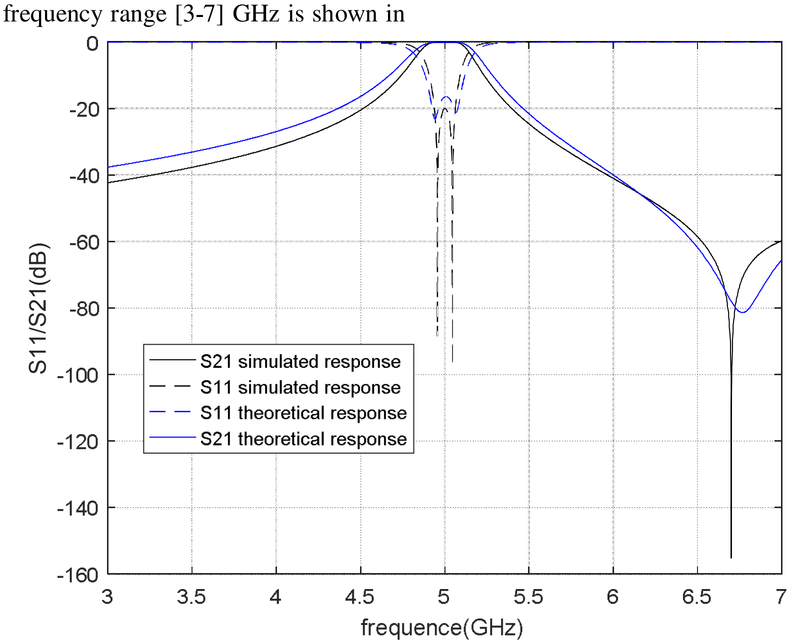

Fig. 10. Frequency response of the inverted E-shaped CSRR bandpass filter.

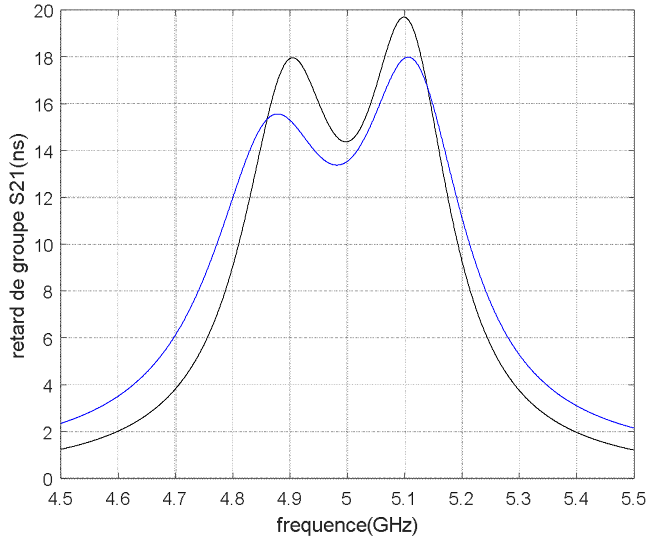

Fig. 11. Group delay response.

Fig. 11 shows a comparison of the theoretical (curve in black) and simulated (curve in blue) responses of the group delay for the inverted E-shaped CSRR bandpass filter. At the center frequency, a difference of 0.84 dB attenuation is observed. Moreover, it is observed a slight shift to the left of the group delay, which is probably due to the presence of the two microstrip transmission lines of the filter in practice, whereas in theory their lengths are neglected.
Also, as expected, group delay is high at the ends of the bandwidth.

In the following Table 3, we have recorded the electrical performance of the square-shaped filter proposed by Yuandan Dong [2] and E-shaped proposed in this article. Note that in order to have a center frequency of 5 GHz, the square-shaped resonator filter proposed by Yuandan Dong has a smaller length and a higher bandwidth and lower insertion losses than the E-shaped resonator filter. Which allows us to say that square shaped CSRR filter is better compared to E from the point of view of compactness and conversely the E shape CSRR filter very selectivity compared to the square shape.

Table 3: Comparison between inversed E and square shape complementary resonators.

Ring shape complementary	Center frequency in GHz	Insertion losses in the bandwidth (dB)	Reflection losses in the passband (dB)	Relative bandwidth width (en %)	Filter length (mm)
Inversed E	5	0.2397	18.41	3.42	4.065
Square shape	5	0.2	20	3.66	3.92

VI. CONCLUSION

In this work, a new bandpass filter structure with integrated waveguide and complementary split-ring resonators is proposed. The filter design was performed using an N + 2 cross-coupled resonator array matrix. This design was analyzed using HFSS software. The compact filter obtained exhibits low insertion losses with good selectivity. The theoretical and simulated filter responses and group delay results were compared, where good agreement was observed. Thenext step will be dedicated to the filter prototyping and experimental validation through measurement.

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