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Conference Article

Full Planar waveguide Design with Complementary Split Ring Resonator and Substrate Integrated Waveguide Technology

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Abstract

Substrate Integrated Waveguide (SIW) technology is a versatile one that combines the excellent performance of a waveguide and the simplicity of a microstrip. These structures are easy to integrate with other planar circuits. In its basic format, SIW some difficulties in the fabrication process, as it requires metal holes drilling. SIW loaded by split ring resonator (SRR) is an appropriate solution as these rings are etched on the substrate's surface, following well-established techniques. In this paper, a comparison between the simple SIW structure, and the SIW-CSRR of a single and a double line is presented, for the frequency band of 24 to 28 GHz, currently used for automotive applications. Excluding the SIW-CSRR of a single line, which has inferior performance, both the other two categories offer an excellent matching below of -20dB and very good Insertion Loss. Split ring resonators SIW technology is proven, therefore, to be a suitable candidate for building millimeter-wave components such as splitters, filters, diplexers and antennas for the 5G circuits.

*Keywords:*Substrate Integrated Waveguide; SIW split ring resonator; microstrip; metamaterial.

1. Introduction

The rapid development of wireless systems for high data rate communications technology are interested in microwave and millimeter novel technologies such as the advent of the Internet of things and fifth generation networks. The technology of next generations drives the community to investigate for new applications. A variety of application has been recently proposed at frequency range over than 90 Ghz, including wearable sensors [1], automotive radar [2], and biometrical devices [3]. The key to the success of this application is to offer low cost, convenient to fabricated systems by planar technique LTCC, PCB with high performance, and complete integration with other wireless systems.

Rectangular metallic waveguides preserves high-quality factor, low loss, and high power handling capability but is bulky and fabricated with non-planar technique. Microstrip and coplanar is planar transmissions lines [4] which fabricated in planar technique but suffered for high losses, especially in high frequencies. Substrate Integrated Waveguides (SIW) [5] is a promising technology which preserves most of the advantages of two technologies fabricated complete circuit system based at passive and active components on the same substrate with flexible and cost-effective technology.

A high interest had been on millimeter-wave SIW component such us power divider, couplers mixers, filters, and antennas suitable to fabricate on system-on-chip fabrication and implementation with other microwave components [6]. SIW need large drill holes, and metalized holes between of substrate require elaborate fabrication process and non-stable structure. An alternative planar waveguide structure has first investigated by [7] replaced metal vias by etched shaped on a surface capable of blocking propagation wave at sides walls offered comparable low losses with conventional SIW structures.

The metamaterials are structures with constant permeability and permittivity that cannot meet in nature [9]. A variety types of metamaterials shapes including metal wires, omega cells, rectangular rings, split ring resonator SRRS can be etched on a metal surface without any significant alternation able to block propagation wave. The most commonly used Split Ring Resonator SRRs provide a negative effective permeability while the Complementary split ring resonator CSRRs exhibit an effective negative permittivity in a narrow band at the resonate frequencies , [8]. CSRRs is the most suitable candidate with properties for a full planar SIW waveguide allowing an easy fabrication process etched on a metal plane. A combination of SIW and CSRR structure first proposed [9] for compact band-pass filters with high performance and controllable characteristics [10-11].

Following the mathematical analysis of the two structures, the scattering parameters results for transmission and reflection will be presented, within the frequency band of 24 to 28 GHz.

2. Design and equation parameter SIW structure

2.1a.SIW General Structure

The SIW features high-pass characteristics, it was

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demonstrated in [6] that a TE_{10}-like mode in the SIW has dispersion characteristics that are almost identical with the mode of a dielectric-filled rectangular waveguide with an equivalent width. The cut of frequency depends on the effective width of the SIW structure 'w' and operate the limited frequency that can use the structure of waveguide. The fabrication of integrated waveguide structures (SIW) is done by integrating two rows of slots or connecting vias on a dielectric substrate to connect the upper and lower metallic layers (Figure 1) by introducing a structure similar to the conventional RWG metal waveguides..

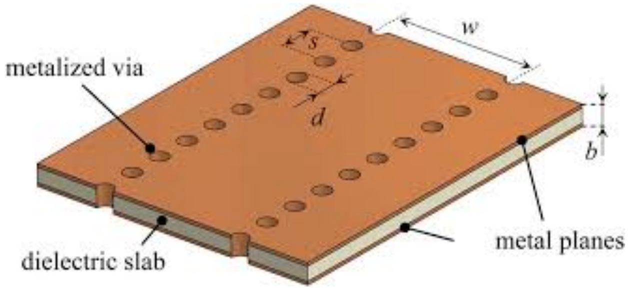

Fig 1. General geometry of SIW [12] .

The behavior of SIW is similar to classic rectangular waveguide (RWG), and the cut off frequency depends on structure width and calculated for dominant mode TE_{10} using the next equation [13].

$$a = \frac{c}{2f_{c10}\sqrt{\varepsilon_r}} \tag{1}$$

α: width of metallic RWG, c: speed of light in free space, fc: cut of frequency, εr: dielectric of substrate.

For waveguide filled with a_d dielectric inside can be obtained with

$$a_d = \frac{a}{\sqrt{\varepsilon_r}} \tag{2}$$

An empirical formula for calculating the SIW width is given by [6] and is called the effective width w (3) as

$$\mathrm{w} = \mathrm{a_d} + \frac{\mathrm{d}^2}{0.95\mathrm{S}} \tag{3}$$

d: diameter of metallic vias, S: distance between two vias.

If the distance between p is too large then leaky radiation losses between metal vias occur. The via diameter may affect the return losses and depends on distance S. To reduce losses must be the following condition:

$$\mathrm{S} \leq 2\mathrm{d} \tag{4}$$

On the other hand, to avoid the band stop condition which occurs over the bandwidth must be defined the following condition [16].

$$\mathrm{d} = \frac{\lambda_\mathrm{g}}{5} \tag{5}$$

$$\lambda_\mathrm{g} = \frac{2\pi}{\sqrt{\frac{\varepsilon_r(2\pi f)^2}{c^2} - \left(\frac{\pi}{a}\right)^2}} \tag{6}$$

where λ_g is the waveguide length of the filled with dielectric substrate waveguide.

2.1b. General Structure of microstrip taper

Microstrip taper and CPW line are widely used transmission medium with other planar structure. Integration SIW with microstrip line design a tapered microstrip line between SIW which match impedance SIW and microstrip for minimum losses [13]. The electric field of TE10 mode at SIW like as microstrip filed that helps to excite the structure. The width of tapered microstrip for reduce losses and matching with 50 Ohm microstrip line computed from the following equations (7-8) [14]

$$\frac{2\pi}{nh\left(\left[\frac{w}{h}+0.393+0.667ln\left(\frac{w}{h}+1.44\right)\right]\right)} = \frac{4.38}{a}\,\mathrm{e}^{-0.627}A \tag{7}$$

$$\mathrm{A} = \frac{\varepsilon_\mathrm{r}}{\frac{\varepsilon_\mathrm{r}+1}{2} + \frac{\varepsilon_\mathrm{r}-1}{2\sqrt{1+\frac{12\mathrm{h}}{\mathrm{w}}}}} \tag{8}$$

where w is the taper width, h height of substrate, ε_r dielectric of substrate, free space impedance$\eta = \sqrt{\mu_0 / \varepsilon_0}$ with μ_0 and ε_0 the permittivity and dielectric constants of the air.

The taper length L is given by

$$\mathrm{L} = \frac{\mathrm{m}\lambda_\mathrm{g}}{4} \tag{9}$$

$$\lambda_\mathrm{g} = \frac{\mathrm{c}}{\mathrm{f}\sqrt{\varepsilon_\mathrm{r}}} \tag{10}$$

where m takes integer numbers i.e 1,2,3,4….

2.2. Design SIW-CSRR Structure

There are many types of electrically small planar resonators. The most famous planar resonator which are fundamental form of design metamaterial structure is the splitring resonator (SRR) figure 2a. SRR is viewed as a parallel resonant has the equivalent circuit in figure 2a. Metallic ring behaves as inductance (L) and the slots between the rings as capacitance (C) [15]. When the SRR is excited by an external time-varying magnetic field along the SRR axis a electric current flow from one ring to another between the slots. SRR has potential applications in the synthesis of metamaterials with negative effective permeability [16]. Based on split-ring resonators (SRR), a negative image complementary plit-Ring resonators (CSRR) were introduced as new metamaterial resonators with negative permittivity.

CSRR behaves as an electric dipole that can be excited by an axial electric field offer stop band properties near at resonator frequency. If the effects of the metal thickness and conducting losses are neglected frequency of the CSRR is identical to the resonance frequency of the SRR. The resonance frequency given by equation (11). In this work, a pair of double rings CSRR facing opposite to each other is used in figure 2.b;

$$f_0 = \frac{1}{2\Pi\sqrt{L_c C_c}} \tag{11}$$

$$Lc = \frac{L_0}{4} \tag{12}$$

$$L_0 = \frac{1}{4}\frac{\mu_o}{\varepsilon}C_0 \tag{13}$$

$$L_0 = 2\pi r L_{pul} \tag{14}$$

$$\mathrm{C_C} = 4\frac{\varepsilon}{\mu_0}\mathrm{L_s} \tag{15}$$

Lpul: per unit length inductance of CPW

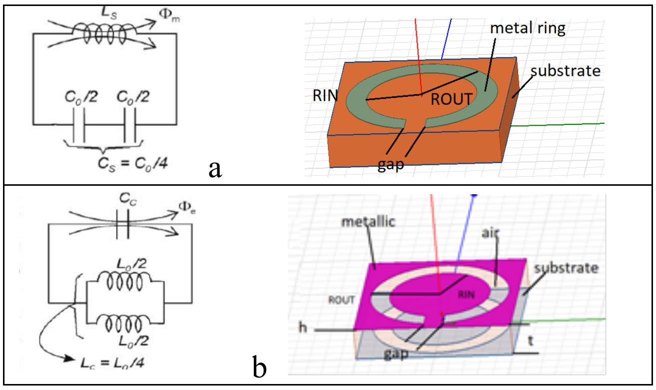

Fig 2.a) Equivalent circuit and design structure a)BC-SRR b) BC-CSRR

Broadside coupled - Complementary Split Ring Resonator proposed are two CSRR etched on the top and bottom metal surface with complementary gaps face towards to opposite direction as shown in Figure 2.b. The BC-CSRR reduced the influence of bi-anisotropic effects separates vertically the two rings.

3. Simulation results and discussion

All structures are designed with substrate material RT/durroid 5880 laminate with a relative dielectric constant ε_r=2,2 and loss tangent tanδ=0.009. The thickness of copper is 0.0017mm. The simulation was performed using the High-Frequency Structure Simulator (HFSS) and mainly focused on minimum propagation losses in the frequency band interest.

3.1 SIW Result

Applying the equations (1) to (6) the design of the cut off frequency for the dominant mode TE_{10}, is calculated to be 22 GHz using the dimensions given in Table1. The effective width set the cutoff frequency and s and d dimensions helps to minimize radiation losses between vias. Figure 3 shows the Transmission (S_{21}) and reflection (S_{11}) scattering parameters confirming the very low transmission losses, and an excellent matching, below -20dB, within the bandwidth of interest. As shown in Figure 3, the cutoff frequency is similar with computed one by equation (1).

Table 1. Most important parameter for SIW Design

Name	Description	Value
d	Diameter of via	0.3 mm
t	Substrate height	0.508 mm
w	Effective width	5 mm
S	Distance between two vias	0.6 mm
nv	Number of vias	15
L	Length of structure	15 mm

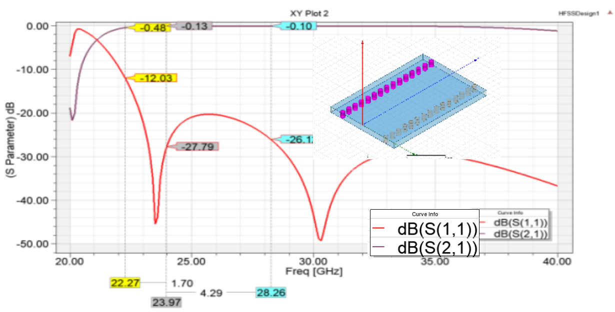

Fig 3. S Parameter (S_{11},S_{21}) SIW structure

In the following sections we use similar dimension for the design of the SIW-CSRR, which helps to compare the performance of the two structures.

3.2 SIW-CSRR Result

Firstly, we analyze S Parameters for single BC-CSRR to find the accurate frequency and how harmonics poles and positive grounds alternative to the resonator. In figure 4 the boundaries conditions are set; Fig. 4. The perfect E perpendicular to resonator is shown Fig 4.b the perfect H side walls of box radiation is depicted, and Fig 4.c is set as wave port in order to excite the BC-CSRR. This way a homogenous electric and magnetic field is created.

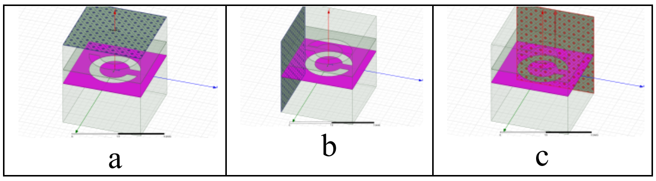

Fig 4. Set boundaries on structure a) Perfect E perpendicular to resonator b) Perfect H side walls and c) set wave port.

The design parameters used for the resonator are presented in Table 2. The reflection coefficient of the structure, S_{11}, and the transmission coefficient, S_{21} are plotted in Figure 5 gives the information of frequency resonator, in this case, the band-stop frequency at 24.10 GHz.

A novel structure with two series of double BC-CSRR at both sides of the SIW is sufficient to replace the metal vias of the basic SIW structure (Fig 1) with low losses. Besides, a single series of BC-CSRR exhibit higher radiation losses at side walls. The design parameters in table 3 behavior over a sufficiently on the frequency range of interest at 24-28GHz with minimal loss slightly larger compared to the conventional SIW, as shown in Figure 6.

Table 2. Design parameter of single BC-CSRR resonator

Name	Description	Value
Rout	External radius	0.3 mm
Rin	Internal radius	0.508 mm
g	Split gap	0.3mm
t	Cooper height	0.017 mm
h	Substrate height	0.508 mm

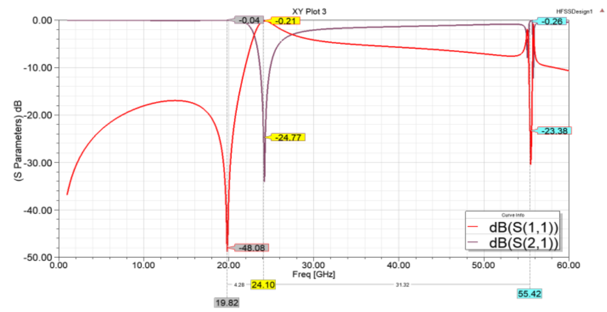

Fig 5. Scattering Parameter (S_{11}, S_{21}) single BC-CSRR structure.

Table 3. Design parameter of SIW-CSRR

Name	Description	Value
Rout	External radius	0.85 mm
Rin	Internal radius	0.5 mm
g	Split gap	0.3 mm
S	Distance between two BC-CSRR	0.1mm
Width	Effective width	6.5 mm
t	Substrate height	0.508 mm

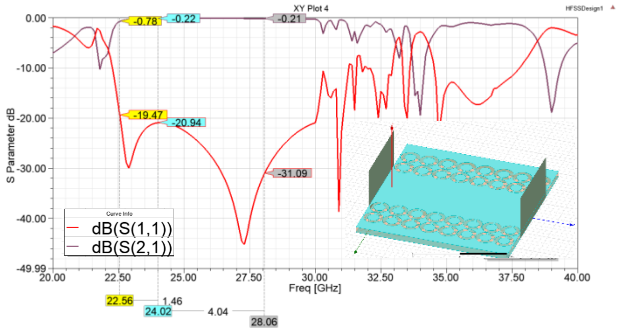

Fig 6. S Parameters S_{11} red line,S_{21} dark line of SIW-CSRR structure

The graphical plots of the electric field confirm for low loss waveguide working at three different frequencies low mid and top of interest bandwidth. In figure 7, the propagation of TE_{10} is shown in three frequencies inside the band, while higher order modes such as TE_{20} are blocked.

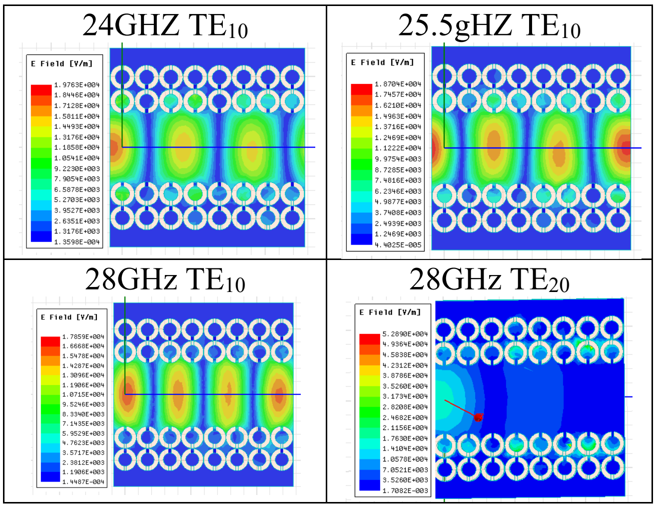

Fig 7. Electric field for three frequency band TE_{10} mode for a,b,c and TE_{20} mode for max frequency.

4. Conclusions

In this work, an alternative waveguide on substrate operating at the 24-28 GHz band is designed using SIW and BC-CSRR resonator. BC-CSRR behaves like an electric dipole suitable to stop the propagation at the resonant frequency, etched on the metal surface of SIW which can replace metallic vias of conventional SIW. SIW-CSRR structure using low-cost commercial materials provide the concept of highly promising fully planar and low profile geometry waveguide fabricated with low-cost PCB technique avoid drilling and metallization process which require high and sophisticated fabrication techniques. In all cases, the analysis of substrate structures using SIW and SIW-CSRR exhibits very low return-loss in the frequency band of interest, below -20dB. The new structure SIW-CSRR exhibits slightly larger transmission-loss compared to the conventional SIW. Compared with the fundamental SIW structure, the SIW-CSRR one is easier to fabricate and control the operation frequency by changing the split-ring dimensions. The penalty to be paid for this, is a narrower band width of operation and more transmission losses, of the order of 0,5dB. Both structures provide an excellent potential framework for designing millimeter-wave sub-circuits and implementing system on chip circuits suitable for the 5G telecommunication networks.

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