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EXAMINE THE DESIGN AND DEVELOPMENT OF SUBSTRATE INTEGRATED WAVEGUIDE CIRCULATORS IN MILLIMETER BANDS OF THE EM SPECTRUM

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***Abstract*—RF and microwave device designers have been interested in ferrite circulators for decades. Circulators are used in satellite T/R modules, radar, and military applications. Early Ordinary Planar Micro strip Circulators featured high insertion, return, and bandwidth losses. In order to get excellent wave transmission characteristics, a waveguide circulator was a good alternative, but due to their non-planar and bulkiness, they are not suitable for modern communication devices and are also not economical, so researchers developed a revolutionary design of rectangular waveguide in planar technology, i.e. RSIW, which has many advantages such as high Q-factor, low loss, relatively high power capacity, and high-density integration of microwaves.**

***Keywords*—RSIW, Q-factor, Microstrip, non-planar, Circulator, T/R module.**

I. INTRODUCTION

The development of low-cost and innovative millimeter-wave transmitter and receiver front ends has sparked unprecedented enthusiasm in both academia and industry [1-3]. This is due to the ever-increasing number of potential applications in broadband wireless communications, high-speed machine-to-machine (M2M) interconnectivity, collision avoidance radar, imaging systems, and countless other wireless sensors and networks. Millimeter-wave methods are widely recognized to give promise in the aforementioned applications due to a range of benefits and distinctive qualities, and this recognition has contributed to the widespread belief that millimeter-wave methods offer promise. Among them are, to name a few: the availability of large bandwidths, which improve spatial resolution for imaging or localization while also increasing data transmission rates for communication; atmospheric attenuation and scattering in connection with various molecular effects (such as rain and fog, for example), which aid in frequency re-use and planning; and wavelength reduction, which reduces system size while increasing antenna array gain. Availability of large bandwidths improves spatial resolution for imaging or localization while also increasing data transmission rates for communication. The criteria for commercial millimeter systems are not limited to performance but also include size and cost, which are the primary barriers to the successful market deployment of a millimeter-wave device or system. In general, the criteria for commercial millimeter systems are not limited to performance. Because transmission line technology is necessary for the creation of high-frequency electromagnetic hardware, choosing an appropriate waveguide or line structure is critical for the advancement and implementation of millimeter-wave technology. The transmission lines that are utilized should make it possible to integrate high densities of components at a reasonable cost and in mass quantities. The development of microwave and millimeter-wave components and systems has made extensive use of rectangular waveguides because of the unique properties that these waveguides possess. These unique properties include a low insertion loss, a high-quality factor (Q-factor), a high power capability, and a number of other advantages. On the other hand, they are characterized by a huge size, a high degree of manufacturing precision, and a form that is not flat. As a direct consequence of this, it is not possible to use this technological platform to develop and build integrated circuits that operate at microwave or millimeter frequencies. Because of their low profile, ease of manufacture, and low cost, microstrip-like circuits, which also include coplanar waveguides (CPW) and strip lines, are now the primary option of integration for the development of microwave and millimeter wave circuits. This is due to the fact that these circuits are similar to microstrips. These printed circuits, unfortunately, suffer from substantial losses in addition to having packaging problems. The bulk of the advantages that are connected to traditional metallic waveguides are preserved in the SIW construction. These advantages include a high Q-factor (low loss) and the capacity to handle high power while maintaining self-consistent electromagnetic shielding. The capacity of SIW technology to permit the total integration of all components on the same substrate, including passive components, active elements, and even antennas [5-9], is the most prominent characteristic of this type of technology. [5-9] SIW methods may be used to treat a wide variety of headache issues, which is likely why they are currently enjoying such widespread acclaim in the medical community [10]. At high frequencies, the presence (trapping) of surface waves can be a significant problem since these waves have a tendency to lower the effectiveness of antennas. The SIW possesses the ability to exercise effective control over this occurrence. SIW components have small insertion loss, extremely low (non-existent) radiation/leakage loss, and are resistant to outside interference since conducting surfaces cover them on both sides of the substrate. In addition, SIW components have a low insertion loss, therefore their overall loss is negligible. More than a decade's worth of time has already resulted in significant progress being made in the SIW technology. The technology behind SIW has made rapid progress over the course of the previous ten years. This development makes it possible to demonstrate and implement innovative passive and active circuits, antennas, and systems at microwave and millimeter-wave circuits with frequency ranges spanning from sub-gigahertz to sub-terahertz. These circuits can operate at microwave and millimeter-wave frequencies. In addition, the SIW methodology may be combined with other SIC platforms in order to build multi-format and multi-function apparatuses and systems [9].

This article introduces SIW. Then, SIW approaches are investigated for Circulator design in various bands of the EM Spectrum, highlighting their merits in the design process. A range of SIW Circulator designs for different spectrums and their applications are illustrated.

II. DESIGNING PROSPECT OF SIW

A. SIW Techniques and Design Basics

SIW is a planar rectangular waveguide-like device created by inserting two rows of conducting cylinders, vias, or slots in a dielectric substrate electrically sandwiched between two parallel metal slabs (Fig. This planarizes the non-planar rectangular waveguide. SIW components may be made using any method, including PCB, LTCC, and photo-imageable.

The operational frequency range is specified by mono-mode propagation of a quasi-TE10 wave, whose cut-off frequency is only tied to the synthesized waveguide's equivalent width 'a' if the substrate thickness or waveguide height is smaller than this width. The next section describes this similar breadth.

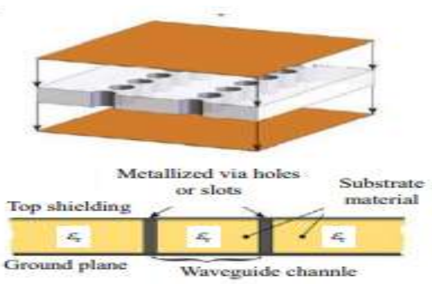

Fig.1 A typical single-layered SIW structure

B. Via configurations

Through two parallel via arrays, round metalized via holes generate SIW's electric sidewalls or fences. The discontinuous current flow along via- or slot-synthesized metalized sidewalls prevents TM mode propagation. SIW's wide width-to-height ratio allows TEm0 modes. SIW may be modelled by a rectangular waveguide (RW) of width a. This value is computed such that the dielectric-filled rectangular waveguide has the same TE10 cutoff frequency as its SIW construction. This affects TE10 mode's propagation. d and p are chosen to minimize radiation (or leakage) loss and return loss [11]. Geometric features can approximate rectangular waveguide width.

Laser micromachining, perforation, and wet/dry etching can also make through arrays. Due to these technologies, circular vias are no longer necessary.

SIW shape replicates rectangular waveguide propagation modes in a narrow template. Modes depend on waveguide width. In a traditional SIW, is the distance between two through rows (see figure). Due to the space between vias and their circular shape, the signal inside the guide does not behave exactly as it would in a fully rectangular waveguide of the same diameter.

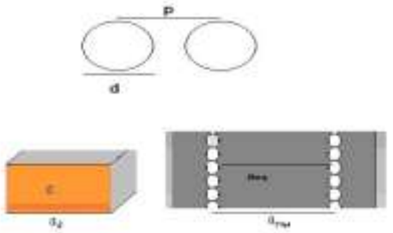

Fig.2 Metalized via and slot arrays for constructing similar metallic fences or walls

$$\mathbf{a_{eq}} = \mathbf{a_{siw}} - \mathbf{d^2}/\mathbf{0.95} * \mathbf{p} \ldots (1)$$

Rectangular slot trenches reduce leakage and define SIW sidewalls. This is important for the iris and window connection geometries in filter design.

Laser micromachining, perforation, and wet/dry etching can also be made through arrays.

Due to these technologies, circular vias are no longer necessary. Rectangular slot trenches reduce leakage and define SIW sidewalls. This is important for the iris and window connection geometries in filter design. Rounded corners enhance mechanical stability and allow for greater metallization, which is important because to laser beam diameter.

C. Substrate materials

Low-loss materials are essential for high-performance ICs and systems. As millimeter-wave frequencies increase, this becomes more essential for power budgets. Certain frequency bands are difficult to amplify. Thermal effect, dielectric non-uniformity, and metallic surface roughness may all affect design. This is crucial for antennas. The SIW may be made from any substrate. Rogers RT/duroid®5880 glass microfiber reinforced PTFE composite and RT/duroid®6002 are often used for PCB processing. They may be sheared with a laser and machined to the appropriate shape. Unlike ceramics, these machinable materials can be drilled mechanically. These materials are dimensionally stable. Design should consider the material's thermal stability.

D. Loss considerations

During transmission, energy is lost due to dielectric, conductor, and radiation losses. Appropriate dielectric material and conductor thickness can reduce the contribution of the first two-loss modes.

Radiation causes signal loss and interference. [11] studied the parametric effects of p and d to provide a radiation less, leakage-free waveguide section. To simplify computations, dielectric and conductor losses are ignored; only radiation loss is considered. To minimize return and leakage losses, the hole's diameter must fulfill certain geometries.

$$\mathbf{d} < \frac{\lambda_g}{5}, \mathbf{p} \leq 2\mathbf{d} \ldots(2)$$

In most cases, planar circuits are affected by radiation at millimeter and sub millimeter frequencies. This radiation is caused by bends and discontinuities in the circuit. [13] looked into the 77 GHz area and analyzed SIW and microstrip bend losses at a 90-degree angle. A 100-ohm circular microstrip line bend with a radius equivalent to the SIW line radius of 2 mm and a substrate of 10 mil is explored with r equal to 2.95. This line bend also has a substrate of 10 mil.

To determine the total losses, just add the conductor losses, radiation losses, and dielectric losses together in a linear fashion.

A representation of the two bends with electric field plots may be found in Fig.3. The results of the simulation for the defined SIW and microstrip bends are presented in Fig.4. In this scenario, the loss at the SIW bend is around 0.12 dB, whereas the loss at the microstrip bend is 0.36 dB, and when the criteria (2) are satisfied, there are no radiation losses from the SIW structure. Radiation is responsible for the vast majority of losses that occur in microstrip.

Fig.3 Distribution of the E-field along SIW and microstrip bends

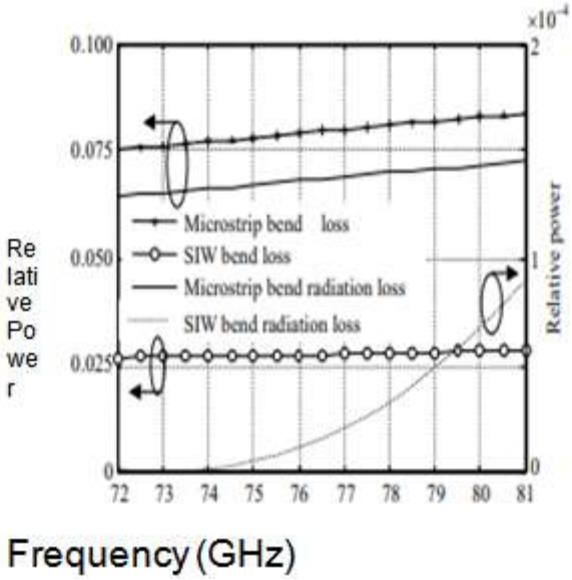

Fig.4 SIW loss and microstrip bends

E. Power handling

Substrate materials and geometric topology have a major role in the SIW structure's average power handling capabilities. In terms of its structural heat endurance and dissipation capacities, and the materials' electric breakdown voltage, which is dependent on substrate thickness and material characteristics, this is a significant factor to consider. Although SIW components are widely used in combination with printed lines, the maximum power handling capabilities of SIW-based circuits are really defined by these printed lines.

The architecture of SIW circuits determines their power handling capability.

Mismatched travel-wave circuit configurations may typically produce significantly more power than their counterparts with mismatched conditions and resonances. Additionally, the microstrip-to-SIW transitions are significantly important for filter design's ability to regulate power [14-15]. When employing the popular Rogers substrate RG5880 with thickness of 0.508 mm, d=0.4 mm, p=0.8 mm, and aeq=15 mm, up to 450 W at 10 GHz for well-matched and non-resonant SIW interconnects and transmission lines may be predicted [16]. This technique has been shown to provide a very attractive and promising power management capability for virtually all known and projected wireless commercial systems.

There are many SIW-based devices and circuits out there, but this section focuses on a few Microwaves Circulator SIW devices and circuits.

SIW-related publications and reports have been found in a number of scholarly journals and conferences so far. These include:

In order to address all that's happened in such a short period of time, this paper will have to be cut short.

II. MICROWAVE CIRCULATOR

A ferrite device with three access points is called a circulator (ferrite is a family of materials with unusual magnetic characteristics). The fact that circulators are not reciprocal is one of their many appealing features. That is, the majority of the energy that goes through port 1 goes through port 2, the majority of the energy that goes through port 2 goes through port 3, and most of the energy that goes through port 3 goes through port 1. The flow of energy in the opposite direction, from port 2 to port 1, would have the same percentage chance of happening as the flow of energy in the first direction.

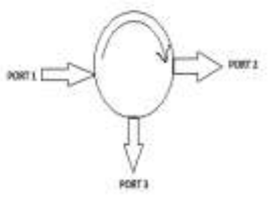

Fig.5 CW circulatorsFig.6 WR-42(Ku-band).. waveguide circulator

Random ports are chosen, and circulators can "circulate" clockwise (CW) or counterclockwise (CC) (CCW).

Waveguide, coax, and "drop-in" microstrip circulators are offered. Microstrip circulators duplex the antenna to the power amp and LNA in T/R modules. Loss and power management are best with waveguide. We found a Ku-band waveguide circulator on eBay.

A circulator, or duplexer, integrates two signals into one channel (e.g. transmit and receive into an antenna). Diplexer refers to a filter that splits two frequency bands into two channels using a single three-terminal device. Many confuse these terms. "Filter" and "diplexer" both have a "I," and "circulator" and "duplexer" both have a "u."

A circulator's isolation should always be defined as its return loss. 20 dB isolation requires 20 dB return loss. Even if the third arm is terminated in 50 ohms, the clockwise isolation in a CCW circulator won't be better than the stray signal bouncing off the loaded port due to the reflected signal's mismatch to 50 ohms.

A. The Wideband Circulator Design Using SIW

[26] was the first article on microwave SIW circulators and isolators. New high-volume applications are integrating SIW circulators [43]. Circulators and isolators have 100 MHz to W-band frequencies (110 GHz). They can be microstrip, coaxial, or waveguide. Waveguide circulators and isolators have superior electrical characteristics. 0.2 dB insertion loss is sometimes possible. Microstrip and coax circulators and isolators have 0.5-1 dB losses. Higher bandwidth means more insertion loss and isolation. As shown in Fig. 22, many applications need the integration of non-planar topologies or the extension of H-plane into E-plane (vertical integration).

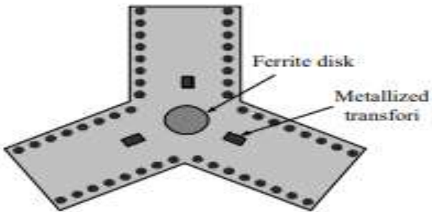

Fig.7 SIW Circulator

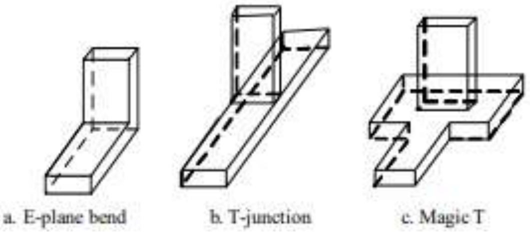

Fig.8 E-plane Structure

B. Design of K-Band Rectangular SIW Circulator

As a result, the dielectric substrate has two metal planes in contact with each other through two rows of holes that are drilled into it.

On high-permittivity surfaces, laser technology may now be utilized to generate any form of small hole. The RSIW, which utilizes two rows of laser-cut metalized square holes to generate vertical electric barriers, has shown to be an excellent choice in terms of insertion losses and bandwidth. Using this method is cheaper than using engraving [7].

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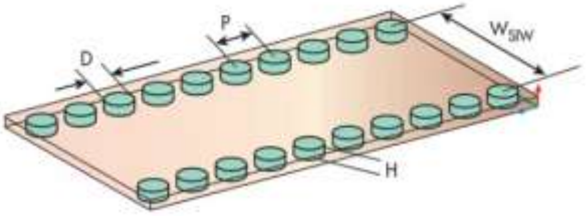

Fig.9 Rectangular waveguide embedded in a substrate RSIW

The side 'd' of the square hole stems, 'p' the spacing between the holes, and's' the spacing between the two rows of holes are all examples of physical elements that contribute to the formation of RSIW (Fig. 9). It follows the equation of [26], and the design from [17] is used to evaluate and develop various components under HFSS merely by knowing the RSIW since the formulae in equations (1) and (2) reveal that there is a constraint in the selection of dimension.

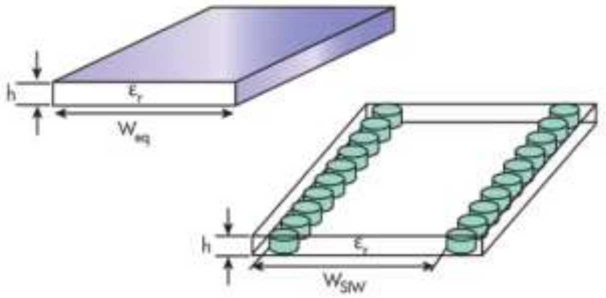

Fig.10 An equivalent rectangular waveguide and RSIW

This research makes it possible to map the electric field associated with the TE10 mode as well as the scatter diagram. When in contact with the metalized conductive planes of the substrate, the rows of holes define a region of electromagnetic wave propagation that is equivalent to that of a metallic rectangular waveguide. Fig.11 illustrates the degree to which the electric field distributions of the TE10 mode in the RSIW and its associated waveguide are comparable to one another.

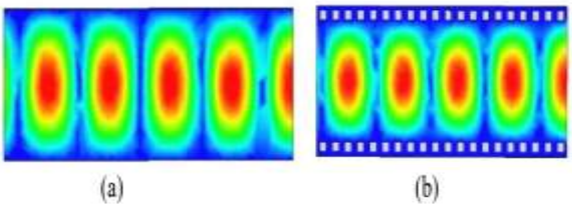

Fig.11 shows the electric field distribution of the TE10 mode in the corresponding rectangular waveguide (a) and the RSIW (b) at f = 22GHz.

The dispersion parameters of these two comparable waveguides are also shown in Fig.(12). According to several research on the features of SIW components [5] technology, only TEn0 modes are transmitted. For millimeter wave frequencies, these components have a broad bandwidth. The dominant TE10 mode's single mode band ranges from 1.25 to 1.9, and the cutoff frequency is [1].

$$f_{c10} = \frac{c}{2W_{eq}\sqrt{\mu_r \epsilon_r}} \ldots (3)$$

In these cases, the permeability r is equal to one. It should be emphasized that this similarity propagation holds true for all TEn0 modes.

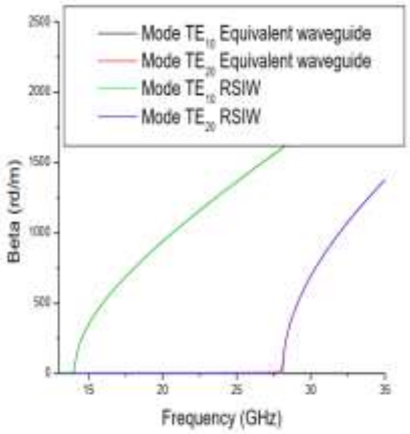

Fig.12 Dispersion characteristics.

In order to improve the reliability of microwave emitters, source protection is widely used and recommended in practice. A wide range of options are available to meet this need. Despite this, circulator waveguide technology [14] still the best option for high-power applications." Non-reciprocity is provided to the circulator through its hexapole structure (Fig. 15), which has three access points spaced 120 degrees apart, with the core body of ferrite (nickel materials and lithium ferrite) being the source of the magnetic field. To prevent received waves from ports 1, 2, and 3 from being transmitted out via access 2, 3, and 1, respectively, a transverse magnetic field is generated in the intermediate region.

$$[S] = \begin{bmatrix} 0 & 0 & e^{j\varphi} \\ e^{j\varphi} & 0 & 0 \\ 0 & e^{j\varphi} & 0 \end{bmatrix}$$

where represents the phase shift introduced by the transmission of the access signal to the subsequent access. The non-symmetry of the matrix clearly demonstrates the non-reciprocity of the component. This non-reciprocity is key to the device's concept and explains why this function may be used in a number of telecommunications applications. This circulator was constructed with square-section rods, and the values in Table I are derived from[17].

Classic wave guide	**Equivalent wave guide**	**Rectangular SIW**	**THE OPTIMAL PARAMETERS**
WR42, a=10.668mm, b=4.318mm, $\epsilon_r = 1$	h=0.254mm, $\epsilon_r = 9.9$ Weq=3.39mm	h=0.254mm, $\epsilon_r = 9.9$, d=0.254mm, p=0.5mm, Wsiw=3.52 mm	LT =5.5mm WT =1.44mm Wmst =0.2mm L= 3.881mm

Table-1

The saturation magnetization of ferrite material in this investigation is [30] 4πMs = 5000 Gauss. It has a radius of [31] and a relative dielectric constant of 13.7.

$$\mathbf{R_f} = \frac{\mathbf{1.84 * Co}}{\mathbf{w_0}\sqrt{\epsilon_f}} \ldots (4)$$

Where Co and Wo are the velocity of light in open space and the operation frequency, respectively [14]. The ferrite height is equal to the thickness of the RSIW, Rf=1.1mm hf=0.254mm.

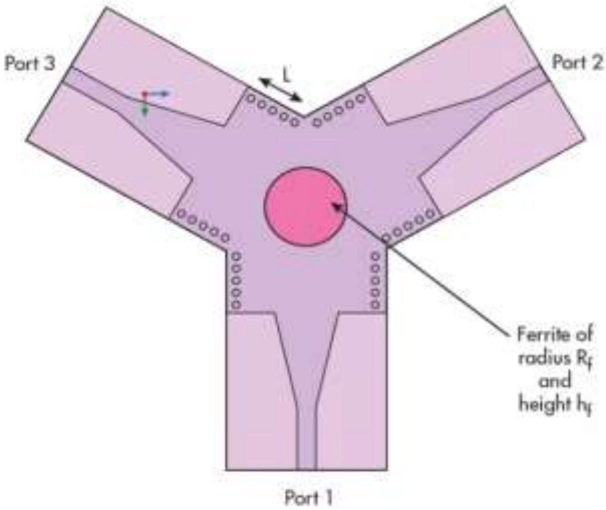

Fig.13 RSIW Circulator

HFSS [27] was used to mimic the RSIW circulator (shown in Fig. 13). The distribution of the electric field of the TE10 mode in the frequency range [18-26.5] GHz is seen in Fig.14.

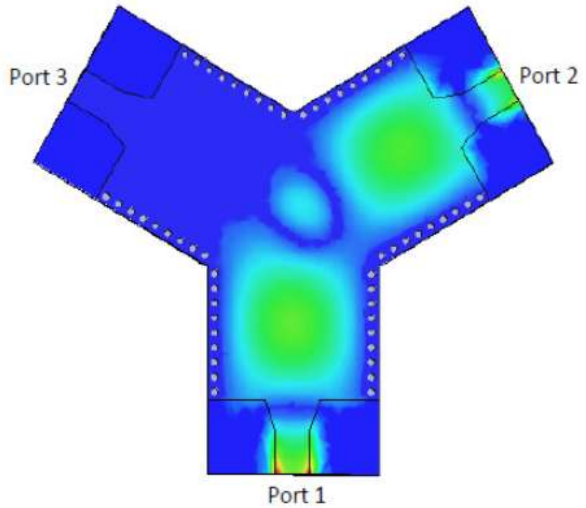

Fig. 14. Electric field distribution of the TE10 mode of the SIW circulator at f = 24 GHz.

Fig.15 shows the frequency response of this SIW circulator, as well as the transmission coefficient S21, reflection coefficient S11, and isolation coefficient S31. The reflection loss S11 below -15dB fills more than 21.75 percent of the bandwidth, the insertion loss S21 is around -0.65 dB, and the highest isolation S31 is -38.11dB, according to the research. Fig. 14 and Fig. 15 confirm the device's circulation property at a frequency of 24 GHz.

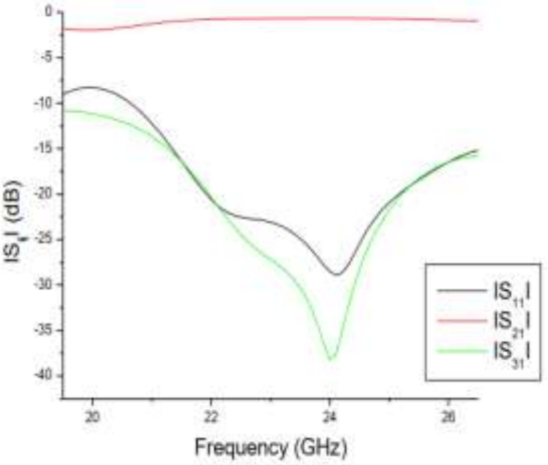

Fig.15 RSIW circulator Sij parameters in k-band

C. Design of Ku-band Rectangular SIW Circulator

Empirical equations [25] were developed to calculate the width of the comparable rectangular waveguide in order to acquire the same properties of the fundamental mode propagating in the RSIW (Fig.2) with the same height and dielectric. Period p must be low in order to reduce leakage losses between adjacent cylinders.

The RSIW [10-15] GHz from a conventional waveguide [29] was investigated in this work, and the feature parameters are listed in Table 2. It [28] derives the parameters of RSIW and the analogous waveguide using the same technique as [25]. (Fig.10) Table No. 2

The saturation magnetization of ferrite material is [30] 4ΠMs = 1250 Gauss in paper [29]. It has a radius Rf determined by [31] and a relative dielectric constant of 13.7. Rf=2.3mm hf=0.8mm is the radius and height of the ferrite.

Classic wave guide	**Equivalent wave guide**	**Rectangular SIW**	**THE OPTIMAL PARAMETERS**
WR75, a =18.35mm b=9.17mm ϵ_r=1	h=0.8mm ϵ_r=2.2 Weq =10.73mm	h=0.8mm, -ϵ_r=2.2, d=0.5mm, p=1mm, WSIW=11mm	LT=2.1mm WT=3.81mm Wmst =2.41mm L=9.016mm

Table-2

In the range [10-15] GHz, the distribution of the electric field of the TE10 mode in the RSIW circulator is similar to that shown in Fig.14, however it is centered for frequency 12.5GHz.

The frequency response of the RSIW circulator is shown in Fig.16, along with transmission coefficients S21, reflection coefficients S11, and isolation coefficients S31. The reflection loss S11 below-15dB occupies more than 10.75 percent of the bandwidth, while the insertion loss S21 is in the range of -0.43 dB, and the isolation S31 is at its maximum of -43.85 dB, according to the results of this study. The two fig14 and 16 corroborate the circulation component's characteristic at a frequency of 12.5 GHz [29].

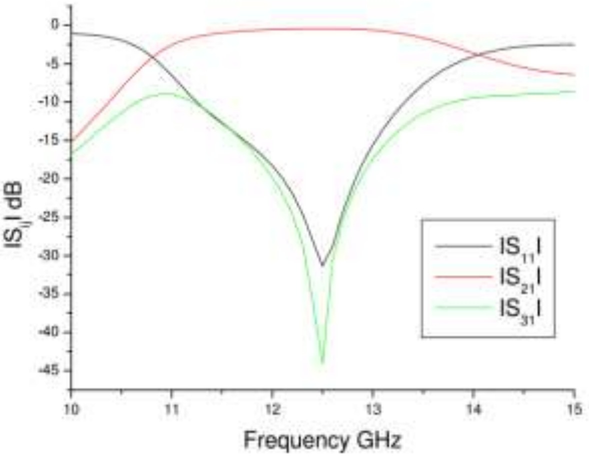

Fig.16 RSIW circulator Sij parameters in ku-band

1) Design of V-Band Rectangular SIW Circulator

Based on the work of Ka-band and Ku-band Substrate Integrated waveguide [17] which is also discussed in earlier sections the modification is done on the dimensional parameter of RSIW in [18] which shows abrupt change in behavior of resonating frequency which sweeps from ka-band to V-band.

Keeping in mind the design equations from [17] the This circulator was created using square-section rods and the values shown in Table.2 which is taken from [18].

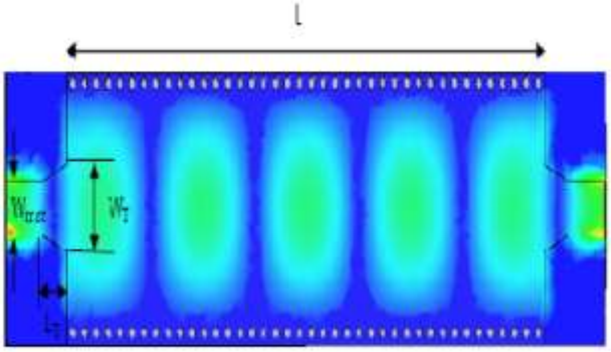

Fig.17: Electric field distribution of the TE10 mode in the matched RSIW at f = 60 GHz.

Classic wave guide	**Equivalent wave guide**	**Rectangular SIW**	**THE OPTIMAL PARAMETERS**
WR15, a =3.759mm, b=1.88mm, ϵ_r=1	h=0.15mm, ϵ_r=3.15, W =2.12mm	h=0.15mm,ϵ_r=3.15, d =0.2mm, p =0.4mm, W =2.24mm	LT =1.57mm WT =0.77mm Wmst =0.37mm L= 2.881mm

Table-3

HFSS [27] was used to mimic the RSIW circulator shown in fig.13. Fig.14 depicts the similar distribution of the electric field of the TE10 mode but in the frequency range [50-75] GHz. Fig.13 depicts the frequency response of this SIW circulator, as well as the transmission coefficient S21, reflection coefficient S11, and isolation coefficient S31. According to the analysis of these results, the reflection losses S11 below -15 dB occupy more than 6% of the bandwidth, the insertion loss S21 is around -0.8 dB, and the maximum isolation S31 is -36.32 dB. The fi validate the device's traffic property at a frequency of 55 GHz [14].

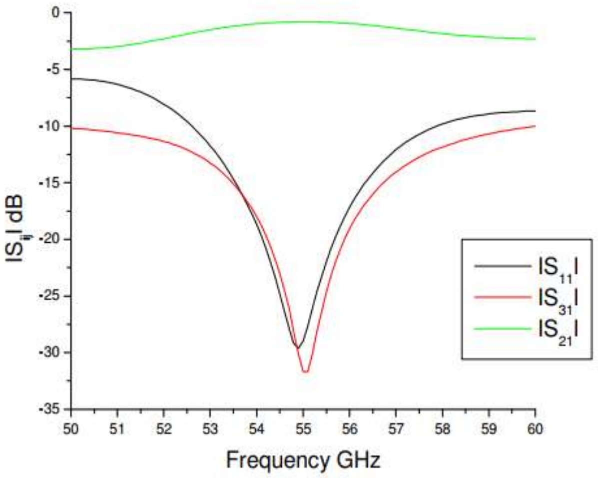

Fig.18 RSIW circulator Sij Parameter in V-band

D. Observation

As we have investigated Rectangular SIW Circulator in three different band i.e. Ku K and V and what we found is that by changing the dimension of Integrated waveguide we have more control on the working frequency and also the losses here we could say that operational frequency is unproportionally changes with the length of Rectangular Substrate integrated waveguide i.e. it initially increases the operating frequency with increase in length of waveguide and then abruptly shift the frequency to lower band and corresponding bandwidth percentage is decreasing with increase in strip to SIW length ratio as we can see for L=3.881mm, LT=5.4mm is 21.75%, for L=9.016mm, LT=2.1mm is 10.75% and for L=2.881mm, LT=1.57mm is 6% which is found in the literature survey and it clearly shows when the L/LT values is greater than 1 and when it keeps increasing then bandwidth also improving impressively and when L/LT values less than '1' then bandwidth is higher in percentage compare to L/LT>1 dimensional Structures. From the above observation it is concluded that the Stripline length LT and waveguide length L are important aspects for the designing of Circulator for the millimeter band spectrum with promising values.

III. ACKNOWLEDGMENT

We would like to express our gratitude to Associate Prof. Dr. Nitesh Kashyap of NIT Jalandhar for his support in selecting and explaining this topic, as well as for donating his time to the discussions. Though they may not agree with all of this paper's interpretations and findings, we are grateful to our colleagues from Dr. BR Ambedkar NIT Jalandhar in Punjab, India, who gave valuable insight and knowledge.

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