Substrate Integrated Waveguide (SIW) Bandpass Filter with improvement of insertion loss and return loss at 2.4 GHz

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Abstract*— This paper presents a design of 2.4 GHz substrate Integrated Waveguide (SIW) bandpass filter using single layer technique on the Printed Circuit Board (PCB). The circular cavity structure using TM_{010} mode for filter is reemployed in the design of this bandpass filter. To realize this concept, the magnitude of E-field distribution for SIW filter resonating at TM_{010} mode is study and analyzed based on the effect of using low permittivity of substrate rogers duroid which is 2.2 and make it air as substrate have a permittivity of 1. The simulation results show a good insertion loss and return loss that prove the concept of low permittivity substrate gives better insertion and return loss. To prove the concept, the SIW filter is fabricated using Rogers Duroid RT5880 with dielectric constant, ε_r =2.2, tangent loss of 0.001, and thickness of 0.787mm. The measured results show good agreement with simulated results. Results show 48.06% improvement (-18.81dB) of return loss (S_{11}) can be obtained from air as substrate compare with Roger Duroid RT5880 has -9.77dB. In the case of make the air as substrate, the insertion loss (S_{21}) is at least 69.57% improvement of -1.05dB compared with Roger Duroid RT5880 which has -3.45dB. The proposed SIW bandpass filter are offer a low profile, low loss, high quality factor, easily to fabricated and integrated with other elements of circuits.

***Keywords*—SIW cavity resonator, microstrip rectangular patch, bandpass filter, SIW microstrip technology.**

I. INTRODUCTION

The wireless communication systems experienced a progressive development in the most recent couple of decades. Many wireless products and service nowadays were introduced due to this invention such as wireless local area network, Global Positioning System (GPS), mobile phone, bluetooth and etc. In this wireless system, both filter and antenna are larger components compared to others [1].

Compact and low loss integrated component are most important element to design and operate in microwave frequency ranges. A waveguide component is an effective way to reduce the cost and improve performances of products and by avoiding transition between the planar circuits such as microstrip circuit [2].

A waveguide technology called the Substrate Integrated Waveguide (SIW) providing low-cost, high-quality, relatively high-power and high-density integration of microwave and millimeter-wave component and subsystem. This waveguide is embedded in the same substrate used in the filter design for the integration of the active part. This SIW technology can be integrated to all active and passive components on a single substrate platform [3].

Substrate integrated waveguide (SIW) is the best and attractive way to alleviate the weight, size and integration issues found from metallic waveguide that have been widely adopted. Lower design, low production cost and easier to integrate with other microwave component and keeping the lower insertion loss are the main advantages of SIW and useful in microwave device. One of the major issues in SIW technology is its losses. The SIW loss mechanisms shows that these structure suffer from ohmic, radiation and dielectric losses. Incomplete shielding of the gaps between vias influences the radiation loss from the possible leaking waves, while the ohmic loss is due to finite conductivity of metal walls, and loss tangent of dielectric material results in dielectric loss. In SIW technology, the dielectric loss is the major source of loss. The decreasing the dielectric loss has significant contributed reduction in total dissipated power in SIW. The main solution in order to achieve the lowest dielectric loss is using air compared by using other dielectric substrate as the transmission medium in SIW [2] [4][5][6].

In addition, transition of microstrip to SIW is used in this structure. The advantages of traditional microstrip circuits such as low cost, easy to fabricate, compact size, less weight and advantages in metallic waveguides such as low loss, complete protecting, higher quality factor and capability of power handling can be merge in SIW technology [7] [8].

There is some limitation of the SIW technique which is in scaling design of via diameter, d and the distance between via hole or pitch, p need to be considered. For a given substrate, the choice of via diameter and spacing between them should be adjusted to provide the best return loss for the transition to the equivalent waveguide. The low return loss requirement can be designed effectively with proper selection of both via diameter, d and the distance between via hole or pitch, p values. The permittivity of substrate material also influences the return loss between the SIW and the equivalent waveguide [4]. While other limitation, in order to get the minimum losses, the SIW structure requires a large diameter of via, d and are has a close together [9].

This paper demonstrates a method to improve return loss and insertion loss of bandpass filter using circular SIW filter. The circular cavity structure using TM_{010} and changes of permittivity substrate material to a lower of permittivity can enhance return loss and insertion loss. The proposed bandpass filter is designed at 2.4GHz center frequency as a prototype and prove of concept. The propagation of the single mode SIW filter by using TM_{010} mode is as the dominant mode. The filter structure with two transitions at ports is designed and simulated using Roger Duroids RT5880 substrate at center frequency 2.4GHz. The advantages using circular TM_{010} mode in SIW technology offers a conventional metallic waveguide with high quality factor, low conductor loss and easily integrated with planar circuitry [10][11]. The method to investigate the effect of return loss and insertion loss results, the substrate is cutting out to imitate air as substrate which has a lower dielectric loss. The cut out radius is applied at the middle of substrate due to E-field concentrated at center of SIW circular cavity [12]. All the simulation process is performed using CST Microwave Studio.

II. METHODOLOGY

In this paper, SIW filter was optimized and fabricated, and measurement results are obtained and compared with simulation results. The flow chart of overall research as illustrated in Fig.1. Filter in microwave device basically is used to reject or isolate specific frequency components. The design of resonant frequency for TM_{010} circular SIW cavity filter is fixed by diameter and is approximated by the following formula [8].

$$\left(f_r^{SIW\ Cavity}\right)_{010}^{TM^Z} = \frac{c}{2\pi\sqrt{\mu_r\, \varepsilon_r}} \sqrt{\left(\frac{2.4049}{a_{SIW}}\right)^2} \quad (1)$$

where μ_r and ε_r are relative permeability and permittivity of the filling material used in SIW resonator. A 2.2 dielectric constant is used for substrate material RT Roger Duroid RT5880 in this design which is having a lower permittivity compared with other available substrate. The substrate which has lower dielectric constant will give better performances other than high dielectric constant of substrate RT Duroid [13]. 2.4049 is the first zero of the Bessel function. The speed of light is denoted as c which is 3.0×10^8. a_{siw} are the radius of the SIW filter. The initial dimensions for the SIW filter are approximated using the above formula and optimized using CST microwave software. In designing the SIW filter, there are design rules for the metalized via hole diameter, d =1mm and the distance between via hole or pitch, p =10mm need to be considered from the following equations [7], [14]. The structure of SIW filters using single layer techniques as shown in Fig.2.

$$d > 0.2\lambda_o \quad , \quad \frac{d}{p} \leq 0.5 \quad (2)$$

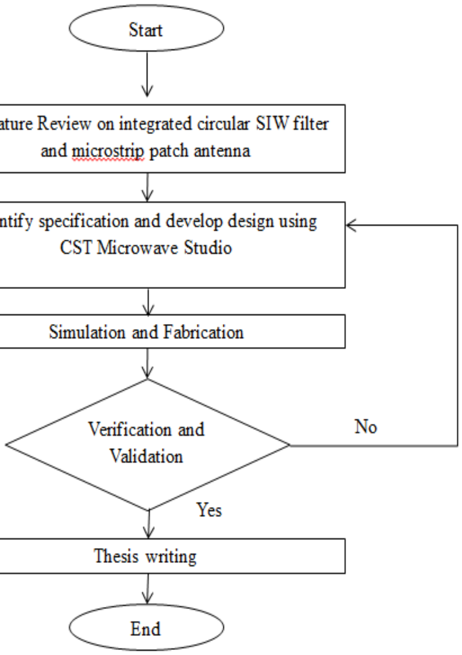


Fig.1. Flow chart for overall research

The single mode TM_{010} circular SIW filter is used to couple energy to microstrip SIW excitation without any external matching circuit. The E-field distribution are symmetric equivalent perfect magnetic wall (PMW) [10]. The structure of SIW bandpass filter is shown in Fig.3 and the geometric dimension as denoted in table 1. The initial parameters of the SIW bandpass filter are chosen using the above formula [15] and calculated for radius SIW cavity is asiw = 32.26mm, and the simulation result shows that the center frequency resonates at 2.33GHz with low return loss, S11 and high insertion loss S21 which is -9.47dB and -3.60dB.

The optimization simulation results shows that when radius SIW cavity is asiw=31.25mm gives the best result for return loss (S_{11}) and insertion loss (S_{21}) which is -9.77dB and -3.45dB and center frequency is at 2.407GHz. Fig.4 shows the simulation results of return loss response at different radius SIW cavity.

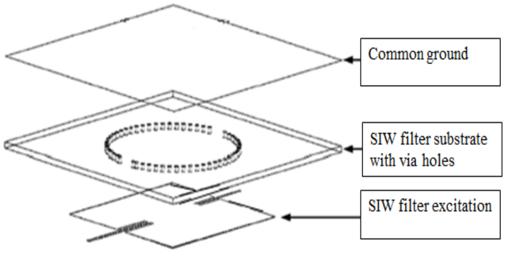


Fig.2. Single layer structure of SIW filter

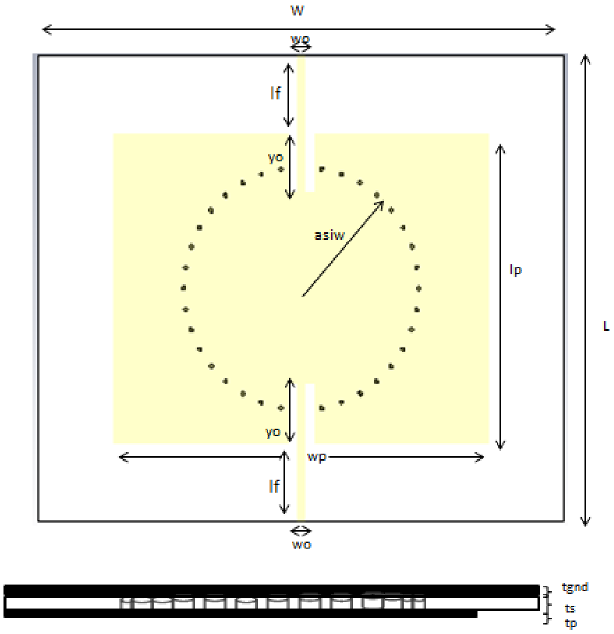


Fig.3. Top view and side view of SIW filter structure

Table 1: Geometric dimension of proposed SIW filter

Variable	**Value (mm)**
length of substrate, L	120
Width of substrate, W	140
Radius of filter, asiw	31.25
length of patch, lp	80
width of patch, wp	100
width of feedline, wo	2.325
length of inset, yo	15.34
length of feedline, lf	21.000031
thickness of substrate, ts	0.787
thickness of patch, tp	0.035
thickness of ground, tgnd	0.035
radius of via, r	0.5

The measured result of return loss (S_{11}) and insertion loss (S_{21}) responses shows a good agreement with the simulated results as shown in table 3 and response of return loss performances as shown in Fig.4.

Table 3: Simulated and measured result of return loss response of SIW cavity using Roger Duroid

Radius SIW Filter, asiw (mm)	**Return Loss, S_{11} (dB)**	**Resonant Frequency, fc (GHz)**	**Insertion Loss, S_{21} (dB)**
31.25 Simulated	-9.77	2.407	-3.45
31.25 Measured	-11.46	2.32	-2.33

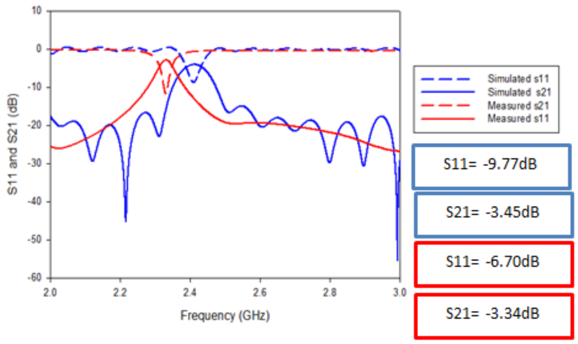


Fig.4: Simulated and measured results of return loss response (S_{11}) and insertion loss (S_{21}) of SIW filter using Roger Duroid

In order to emulate the substrate as air, the whole substrate within the via hole cavity near the SIW metallic is cut out, so only air and ground appear on the design as illustrated is Fig.5. The cut out radius, rc = 29.90mm is chosen and the radius of SIW filter, asiw is fixed to 31.25mm and geometric dimension for proposed SIW filter with holes and ground near the SIW metallic via as shown in table 4 in which our concept is to make the substrate as air, however this investigation is still maintaining the same SIW radius cavity as before. Therefore, we can see the effect of cutting the substrate out to the performances of the filter. The diameter of via hole is 1mm and spacing between them is 10mm and still cut through on the Roger Duroid.

No results measured responses due to fabrication errors, and simulation results after cut out radius as shown in Table 4. The simulated results as shown in Fig.6 shows that the resonant frequency resonate at 3.57GHz with enhancement of return loss (S_{11}) of -29.15dB and insertion loss (S_{21}) of -0.35dB compared by using substrate Roger Duroid which is the return loss (S_{11}) is -9.77dB and insertion loss (S_{21}) is -3.45dB. The inset excitation structure is used to feed the filter. The resonant frequency is expected to be shifted from 2.4GHz due to the change of substrate material by removing dielectric substrate to make the air-cut region between metallic via. The proposed for the air-cut region is nearly the circular cavity SIW structure for more magnitude of E-field concentrated at the center of SIW filter.

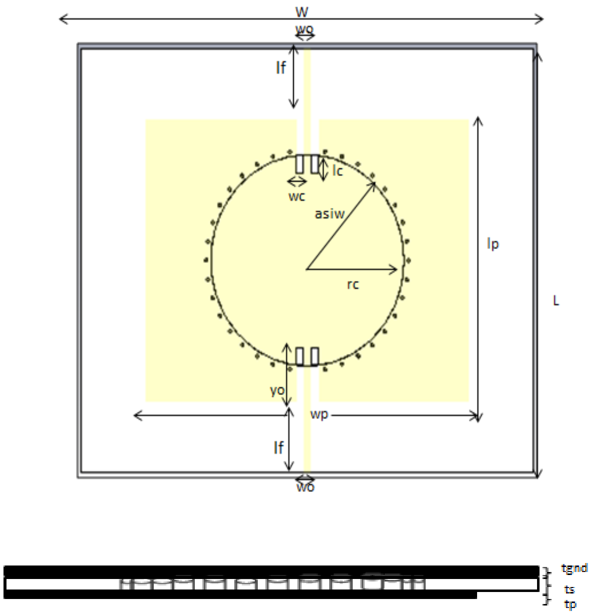


Fig.5. Top view of proposed SIW filter structure with cut out radius

Table 3: Geometric dimension of proposed SIW filter with cut out radius

Variable	Value (mm)
length of substrate, L	120
Width of substrate, W	140
Radius of filter, asiw	31.25
length of patch, lp	80
width of patch, wp	100
width of feedline, wo	2.325
length of inset, yo	15.34
length of feedline, lf	21.000031
thickness of substrate, ts	0.787
thickness of patch, tp	0.035
thickness of ground, tgnd	0.035
radius of via, r	0.5
cut out radius, rc	29.9
width of cut out, wc	2.325
length of cut out, lc	4.94

Table 4: Simulated and measured results for air as substrate

Radius SIW Filter, asiw (mm)	**Cut out radius, rc (mm)**	**Return Loss, S_{11} (dB)**	**Resonant Frequency, fc (GHz)**	**Insertion loss, S_{21} (dB)**
31.25 Simulated	29.9	-29.15	3.57	-0.35

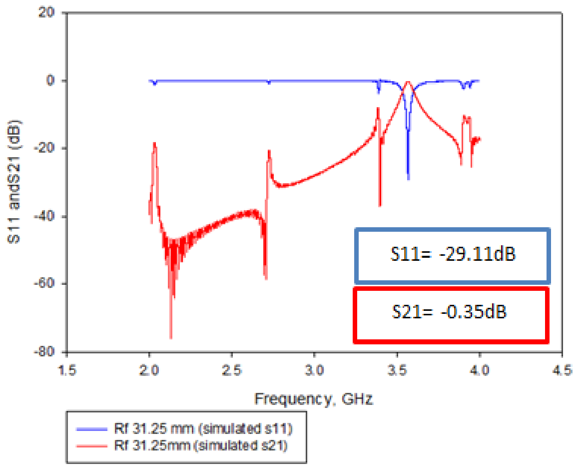


Fig.6. Simulated results of return loss response (S_{11}) with cut out of radius

To obtain the center frequency at 2.4 GHz, the new geometric dimension for proposed SIW bandpass filter is constructed as illustrated in table 5. The structure of new geometric dimension of filter designed is 210mm X 150mm. The radius of SIW cavity, asiw is recalculated based on formula (1) when using permittivity of air is 1 to make the substrate as air. The new radius SIW cavity is 47.84mm. The new radius of cut, rc =47.34mm. The new variables are simulated via CST microwave software. The best results after optimization process is obtained when asiw is 49.14mm and the cut out radius, rc is 48.00mm with good return loss (S_{11}) and insertion loss (S_{21}) which is -18.81dB and -1.05dB at center frequency is 2.40GHz.

Table 5: The new geometric dimension of proposed SIW filter with cut out radius

Variable	Value (mm)
length of substrate, L	150
Width of substrate, W	210
Radius of filter, asiw	49.14
length of patch, lp	120
width of patch, wp	150
width of feedline, wo	2.325
length of inset, yo	15.34
length of feedline, lf	15
thickness of substrate, ts	0.787
thickness of patch, tp	0.035
thickness of ground, tgnd	0.035
radius of via, r	0.5
cut out radius, rc	48
width of cut out, wc	2.325
length of cut out, lc	3.31

Table 6: Simulated results for proposed SIW filter

Radius SIW Cavity, asiw (mm)	**Cut out radius,rc (mm)**	**Return Loss S_{11} (dB)**	**Resonant Frequency, fc (GHz)**	**Insertion loss S_{21} (dB)**
49.14 Simulated	48.00	-18.81	2.40	-1.05

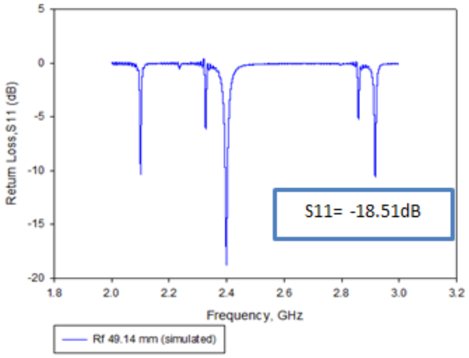


Fig.7. Simulated results of return loss (S_{11}) response for proposed SIW filter

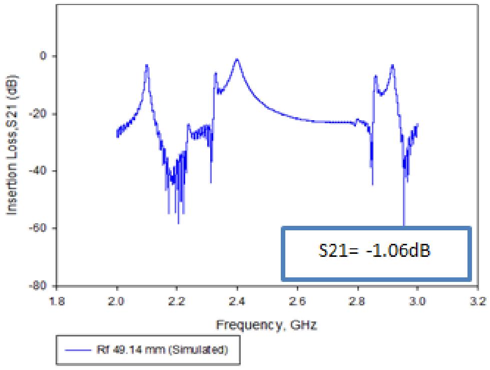


Fig.8. Simulated results of insertion loss (S_{21}) response for proposed SIW filter

Table 6 shows the simulated results of return loss and insertion loss response of proposed SIW filter at center frequency 2.4 GHz. No result for measurement of proposed SIW filter due to fabrication errors. The simulation results of return loss (S_{11}) and insertion loss (S_{21}) responses as shown in Figure 3.6 and Figure 3.7. The most significant result of return loss response (S_{11}) at resonant frequency 2.40 GHz is -18.81 dB, while the result of insertion loss (S_{21}) response is -1.05dB.

III. PARAMETRIC STUDY

A parametric study on the return loss (S_{11}) and insertion loss (S_{21}) of SIW bandpass filter was conducted using different size of radius of cut near the SIW circular cavity.

A. The cut out radius

The parametric study of cut out radius, rc is simulated and measured in order to get the best return loss (S_{11}) and insertion loss (S_{21}) of SIW bandpass filter. The result of parametric study as illustrated in Table 7. Based on the simulation, the best cut out radius, rc is 48.00mm which gives the best return loss (S_{11}) and insertion loss (S_{21}).

Table 7: Parametric study results for different cut out radius

Cut out radius, rc (mm)	**Return Loss S_{11} (dB)**	**Resonant Frequency, fc (GHz)**	**Insertion loss S_{21} (dB)**
5	-5.94	2.40	-5.74
10	-5.97	2.39	-5.70
15	-5.96	2.39	-5.71
20	-10.11	2.39	-3.58
25	-10.09	2.39	-3.58

30	-5.94	2.39	-5.73
35	-5.94	2.40	-5.73
40	-5.95	2.40	-5.74
45	-5.97	2.39	-5.70
46	-10.05	2.40	-3.59
47	-5.99	2.39	-5.68
48	-5.93	2.40	-5.75
45	-18.94	2.40	-1.08
46	-18.53	2.40	-1.03
47	-5.92	2.40	-5.76
48	-18.81	2.40	-1.05

Fig.9 shows optimization result of return loss response with different cut out radius. The size of radius of cut out radius varies from 5.00mm to 48.00mm and return loss (S_{11}) shows that the larger of radius of cut gives better performances of SIW bandpass filter which is -18.81dB compared with other cut out radius. This also shows more E-field concentration at center of SIW circular cavity. Two sample data from the parametric study of cut out radius, rc which is 20mm and 45mm is simulated and measured. The results of these two sample data as denoted in Table 9. The radius of SIW filter, asiw = 49.14mm. No measurement results for rc=45mm due to fabrication problem. The measured results for rc=20mm shows high losses in return loss and insertion loss results compared with simulation ones. Fig.10 shows simulation results of return loss response for rc=20,45mm and simulated and measured results of return loss and insertion loss response when rc=20mm. At 2.4 GHz the best results of return loss response when the cut out radius value is larger compared with small cut out radius to make the air as substrate.

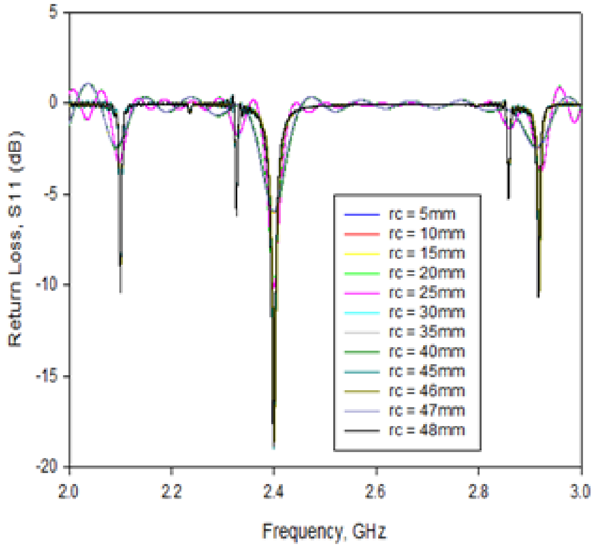
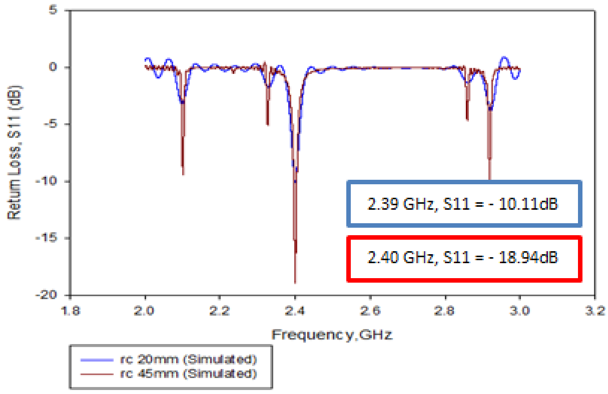


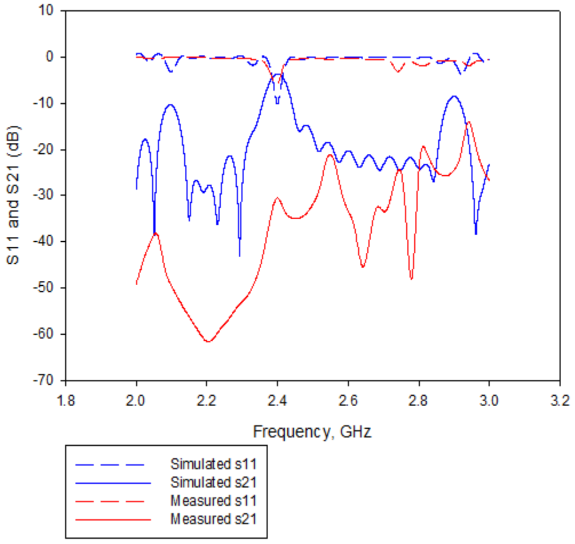
Fig.9. Optimization results of return loss response with different radius of cut and

Table 9: Simulated and measured sample results of parametric study

Cut out radius, rc (mm)	**Return Loss S_{11} (dB)**	**Resonant Frequency, fc (GHz)**	**Insertion loss S_{21} (dB)**
20 Simulated	-10.11	2.39	-3.58
20 Measured	-5.72	2.39	-30.71
45 Simulated	-5.97	2.39	-5.70



(a)



(b)

Fig.10. (a) Simulated of return loss response for sample results of parametric study and (b) simulated and measured results for rc is 20mm.

IV. RESULTS AND DISCUSSION

The design of SIW bandpass filter is constructed using RT Roger Duroid RT5880 with dielectric thickness 0.787mm for SIW filter. The dielectric constant of the substrates Rogers Duroid is ε_r =2.2 and the loss tangent is 0.001. The magnitude of electric field for SIW bandpass filter at 2.4GHz is shown in Fig.11. It shows the magnitude of the E-field is concentrated at the center of the SIW cavity because it is operating at TM_{010} mode.

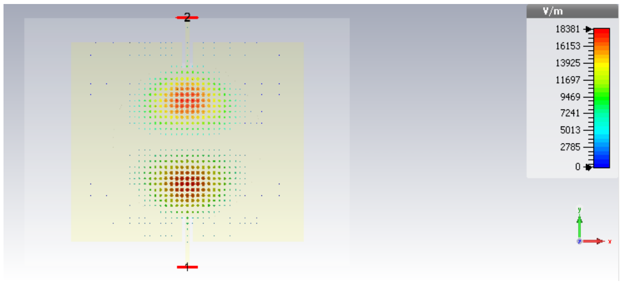
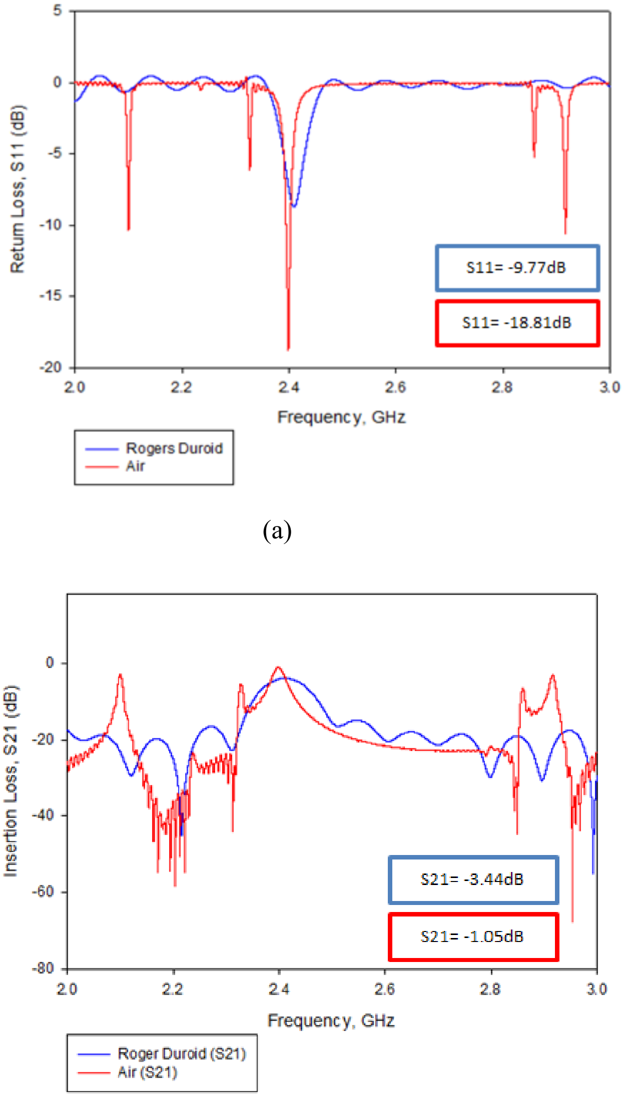


Fig.11. E-field distribution of SIW bandpass filter at 2.4GHz

The response of return loss (S_{11}) of the SIW bandpass filter with different substrate material Rogers Duroid and air which is different permittivity values is shown in Fig.12. Based on the graph, it is observed that the good return loss (S_{11}) and insertion loss (S_{21}) is obtained by using air as substrate material which is -18.81dB and -1.05dB at center frequency 2.4 GHz as describe in Table 10.

Table 10: Comparison simulated results of return and insertion loss using different substrate material

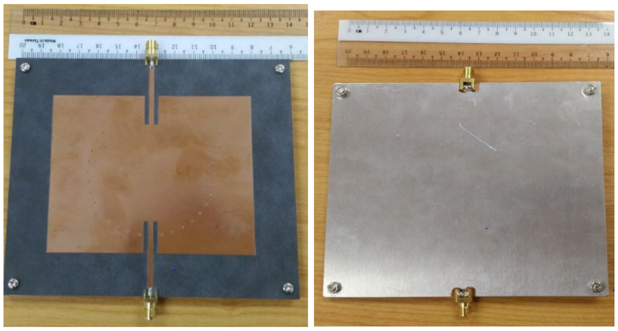
Substrate material	**Radius SIW Cavity, asiw (mm)**	**Return Loss, S_{11} (dB)**	**Resonant Frequency, fc (GHz)**	**Insertion loss, S_{21} (dB)**
Roger Duroid, ε_r =2.2	31.25	-9.77	2.407	-3.45
Air, ε_r =1	49.14	-18.81	2.40	-1.05



(a)

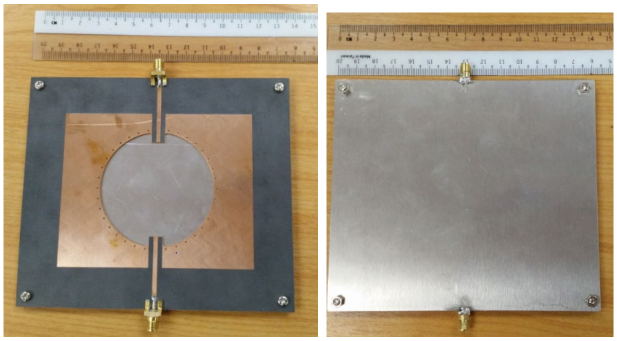
(b)

Fig.12. Comparison of (a) return loss (S11), (b) insertion loss (S21) responses between Roger Duroid and Air as substrate material



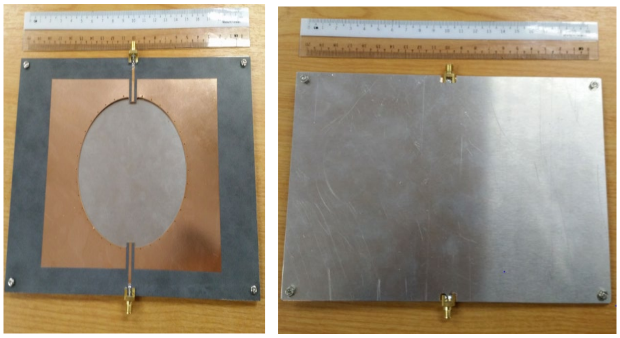
(a) (b)

Fig.13. Photograph of the fabricated SIW bandpass filter using Roger Duroid for dimensions 140mm x 120mm. (a) Top view, (b) bottom view



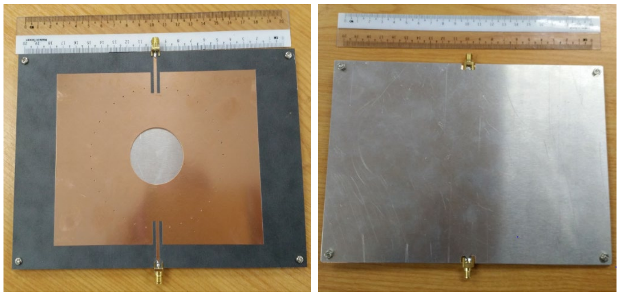
(a) (b)

Fig.14. Photograph of the fabricated SIW bandpass filter with cut out radius for dimensions 140mm x 120mm. (a) Top view, (b) bottom view

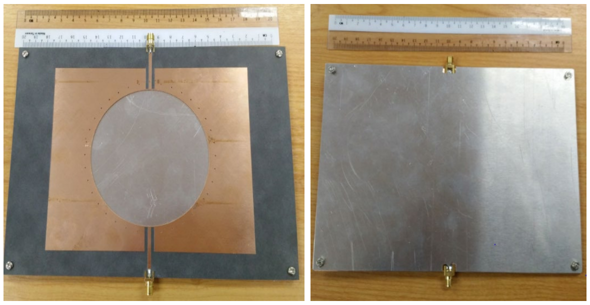


(a) (b)

Fig.15. Photograph of the fabricated proposed new SIW bandpass filter with cut out radius for dimensions 210mm x 150mm. (a) Top view, (b) bottom view



(a)



(b)

Fig.16. Photograph of the top and bottom fabricated proposed new SIW bandpass filter with different cut out radius for dimensions 210mm x 150mm. (a) rc = 20mm, (b) rc = 45mm.

Fig.13 presents two photograph of the top and bottom view fabricated SIW bandpass filter with dimension of width and length of 140mm x 120mm using Roger Duroid. Fig.14 shows the fabricated design with cut out radius to imitate air as substrate with dimension of width and length of 140mm x 120mm. Fig.15 presents two photograph of the top and bottom view fabricated proposed new SIW bandpass filter with dimension of width and length of 210mm x 150mm. The cut out radius is 48mm to imitate air as substrate. Fig.16 shows the two photograph of the top and bottom view fabricated proposed new SIW bandpass filter with different cut out radius of 20mm and 45mm. All the fabricated design is using aluminium plates as a ground with the thickness is 20mm.

The improvement of return loss (S_{11}) can be obtained about 48.06% from air as substrate material compared with RT Roger Duroid RT5880. The higher improvement is observed in insertion loss (S_{21}) which is 69.57% by using air as substrate material in SIW bandpass filter as compared to Roger Duroid substrate. The high radius of SIW cavity is obtained from substrate air which is suitable for low frequency 2.4GHz.

However, the measured result exhibits decrease in passband return loss value as it is believed due to complex design and fabrication process. This shift is however considered small and was probably due to errors which occurred during fabrication process and errors in the substrates dielectric constant.

V. CONCLUSION

A novel SIW bandpass filter material concept has been presented in this paper. It is proven that air is better substrate and can be obtained through simulation and can be realized through altered fabrication technique. The simulated performance of the device shows an acceptable agreement with the experimental results. Consider the reasons of the errors, the untight stacking of the SIW cavity and aluminium plate at ground plane resulting in presence of gap cause to high energy losses effect the efficiency of the filter device. Also the metallic vias used were not perfect conductors, seems they have different values of dielectric, while the dielectric of PEC is infinite. With a good fabrication process, the SIW bandpass filter can give a better performance. Therefore, this filter device is suitable to be integrated with antenna and implemented in wireless communication products.

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