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Design and Realization of Band Pass Filter in K-Band Frequency for Short Range Radar Application

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Abstract

Short range radar (SRR) uses the K-band frequency range in its application. The radar requires high-resolution, so the applied frequency is 1 GHz wide. The filter is one of the devices used to ensure only a predetermined frequency is received by the radar system. This device must have a wide operating bandwidth to meet the specification of the radar. In this paper, a band pass filter (BPF) is proposed. It is designed and fabricated on RO4003C substrate using the substrate integrated waveguide (SIW) technique, results in a wide bandwidth at the K-band frequency that centered at 24 GHz. Besides the bandwidth analysis, the analysis of the insertion loss, the return loss, and the dimension are also reported. The simulated results of the bandpass filter are: VSWR of 1.0308, a return loss of -36.9344 dB, and an insertion loss of -0.6695 dB. The measurement results show that the design obtains a VSWR of 2.067, a return loss of -8.136 dB, and an insertion loss of -4.316 dB. While, it is obtained that the bandwidth is reduced by about 50% compared with the simulation. The result differences between simulation and measurement are mainly due to the imperfect fabrication process.

Keywords: Short Range Radar, Band Pass Filter, Microstrip, Substrate Integrated Waveguide, K-Band.

I. INTRODUCTION

K-band frequency range is attractive for a small size radar that is used for an application that does not require long-range detection. In the original K-band, there is a water vapor absorption line at 22.2 GHz which causes a serious problem of attenuation in some applications. The radar echo from rain can limit the capability of radars at these frequencies [1]. Therefore, the K-band at 24 GHz can be utilized in several fields such as in the automotive industry for detecting small objects at close range or short-range radar (SRR) application [2] [3].

SRR on the K-band requires a wide bandwidth, especially for automotive radar applications, because the high resolution of the SRR system with a wide bandwidth is able to detect surrounding objects and predict the direction of speed of these objects. A wide bandwidth property is very important for the safety factor of the vehicle because it can predict and avoid accidents that may occur. Meanwhile, if an SRR uses a narrow bandwidth, the radar may unable to detect the direction of the object approaching a vehicle. This is due to the radar's inability to detect an object that is close to each other, increasing the risk of an accident.

There are several devices that are part of the SRR system, one of which is the filter. Therefore, a filter with certain specifications is needed so it can be used in SRR

systems. To have a filter design with a low insertion loss, small size, and limited cost is essential for the manufacture of microwave systems. Unfortunately, the traditional technology, either planar or non-planar, is incapable to provide all these characteristics at the same time. In fact, the rectangular waveguides present low insertion losses and good selectivity [4]. Recently, a substrate integrated waveguide (SIW) is one popular method to design microstrip filters. This method is similar to the conventional rectangular waveguide, and can be used in the K-band frequency range in order to meet the bandwidth and filter characteristics requirement, including insertion loss, return loss, and minimization of filter dimensions. Figure 1 shows the similarity of the electric field distribution in the SIW and equivalent conventional waveguide.

In the SIW filter structure, the via sequences are connected between the top and bottom of the conductor forming a cavity wall, where the microstrip transmission line is used for the feeding of the RF input and output. The cavity wall consists of via rows that provide out-of-band rejection, making it perfect to be used in radar applications [5]. Basically, the microstrip transmission line is also functioned to guide a signal that enters a device. However, the thing that makes SIW different from other microstrips is the presence of the two rows of

metal cylinders, causing low-frequency signals to not propagate in the SIW [6]. Also, a wide operating bandwidth can be achieved using the SIW, as reported in [7], [8]. In [7], a hybrid and periodically drilled SIW (PDSIW) structure are proposed. While in [8], a substrate integrated plasmonic waveguide (SIPW) concept is used to obtain a wide bandwidth.

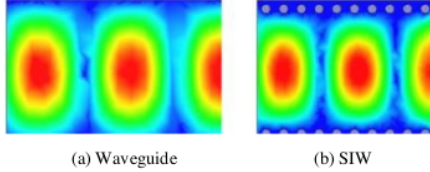


Figure 1. Comparison of Waveguide and SIW Filter [9].

In this paper, a design of wideband band pass filter (BPF) using the SIW technique is proposed. The device is designed and fabricated on R3003C substrate. This BPF will operate at the K-band with a center frequency of 24 GHz.

II. FILTER DESIGN AND SIMULATION

A. Design Methodology

The proposed design of bandpass filter is intended to pass signals at the center frequency of 24 GHz with a bandwidth of 1 GHz. The bandpass filter is designed as a part of the SRR block system. The flow chart of the design stages is depicted in Figure 2.

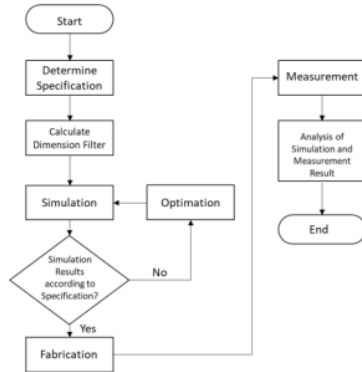


Figure 2. Flowchart of Filter Design.

In Figure 2, a filter design steps to determine the filter specifications until the realization phase is shown. Filter performances must meet the value of certain parameters such as insertion loss, return loss, and VSWR.

The filter specifications are as follows:

- Frequency Range : 23.5 GHz – 24.5 GHz
- Center Frequency : 24 GHz
- Bandwidth : 1 GHz
- Return Loss : ≤ -10 dB
- Insertion Loss : ≥ -3 dB
- VSWR : ≤ 2
- Frequency Response : Chebyshev
- Substrate : Rogers RO17C (Thickness: 0.813 mm) (Dielectric Constant (ϵ_r): 3.55)

After determining the specifications, next step is to calculate the dimensions of the filter. This includes determining the order, the diameter, and the distance between the vias, using a predetermined formula. The next stage is to simulate the calculation of the filter dimensions in the previous stage.

In the simulation phase, the S-parameter values will be obtained. If the simulation results are not in accordance with the specifications, optimization will be carried out, but if the simulation results have met the requirements, the filter design will be fabricated. The filter that has been fabricated will then be measured and compared with the simulation results. Then, the difference between the two results will be analyzed.

B. Substrate Integrated Waveguide (SIW)

The characteristics of SIW are similar to that of a rectangular waveguide. The combination of a non-planar circuit (waveguide) and a planar shape (microstrip) offers various advantages, namely the characteristics of a non-planar waveguide can be obtained from SIW structures such as low insertion loss, low radiation loss, small EM interference, and low-cost fabrication.

The thin dielectric substrate on SIW does not allow transverse magnetic (TM) mode to resonate. Therefore, in SIW only the transverse electric (TE) mode can transmit effectively [10] [11]. In Figure 3 there are several important parameters to form the via wall. To find the diameter of the via, the distance between the via series, and the distance between the rows, following equation is used [12].

$$d < \frac{\lambda_g}{5} \quad (1)$$

$$p \leq 2d \quad (2)$$

$$a = \omega - \frac{d^2}{0.95 \cdot p} \quad (3)$$

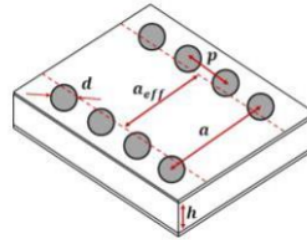


Figure 3. Via Structure on Substrate Integrated Waveguide [13].

SIW filter can be designed using additional set of vias that is placed between the via walls. Figure 4 shows the parameters of the diameter and distance between the vias.

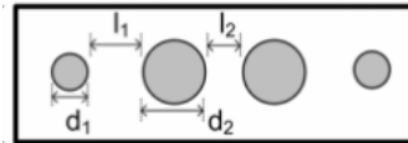


Figure 4. Structure of the Via Filter [14].

To find these parameters, the following equation is used:

$$\omega = \frac{\omega_2 - \omega_1}{\omega_0} \quad (4)$$

$$\omega\lambda = \frac{\lambda G}{\lambda_0} \omega \quad (5)$$

after that, substitute the values in equations (4) and (5) as the parameters in the Chebyshev frequency response, in equations (6) and (7) [14].

$$\frac{K_{01}}{Z_0} = \frac{K_{34}}{Z_0} = \sqrt{\frac{\pi}{2} \frac{\omega\lambda}{g_{01}g_{1\omega_1}}} \quad (6)$$

$$\frac{K_{12}}{Z_0} = \frac{K_{23}}{Z_0} = \frac{\pi \omega\lambda}{2\omega_1} \frac{1}{\sqrt{g_1g_2}} \quad (7)$$

Then substitute equations (6) and (7) into equation (8). This equation calculates the final impedance for each stage in equations (6) and (7) [14].

$$\frac{X_{jj}}{Z_0} = \frac{K_{jj+1}/Z_0}{1 - [K_{jj+1}/Z_0]^2} \quad (8)$$

The dimensions of the via filter can be determined using the following equation. [14]

$$\theta_j = \pi - \frac{1}{2} \left[\tan^{-1} \left[\frac{2 \cdot X_{jj+1}}{Z_0} \right] + \tan^{-1} \left[\frac{2 \cdot X_{jj+1}}{Z_0} \right] \right] \quad (9)$$

$$l_1 = l_3 = \frac{\theta_1 \cdot \lambda_g}{2\pi}, l_2 = \frac{\theta_2 \cdot \lambda_g}{2\pi} \quad (10)$$

To match the impedance between the feed and the SIW components, a taper is introduced to connect these two. The dimensions of the taper can be determined using equations (13) and (14) [13].

$$f_{TE10_{SIW}} = \frac{c}{2\sqrt{\epsilon_r}} \left(a - 1.08 \frac{d^2}{p} + 0.1 \frac{d^2}{a} \right)^{-1} \quad (11)$$

$$f_{TE20_{SIW}} = \frac{c}{\sqrt{\epsilon_r}} \left(a - \frac{d^2}{1.1p} + 0.1 \frac{d^2}{6.6p^2} \right)^{-1} \quad (12)$$

$$lf2 = \frac{2c}{3(1.25 \cdot f_{TE10_{SIW}} + 0.95 \cdot f_{TE20_{SIW}}) \sqrt{\epsilon_r}} \quad (13)$$

$$wf2 = \frac{c}{3(1.25 \cdot f_{TE10_{SIW}} + 0.95 \cdot f_{TE20_{SIW}}) \sqrt{\epsilon_r}} \quad (14)$$

Before determining the dimensions of the filter, the first thing to consider is the order of the filter to be used. Based on the specifications, the most suitable frequency response is Chebyshev, with a ripple of 0.1 dB. To determine the filter order (n), following equations are used:

$$FBW = \frac{\omega_2 - \omega_1}{\omega_0} \quad (15)$$

$$\Omega s = \frac{2}{FBW} \left(\frac{\omega_2 - \omega_1}{\omega_1} \right) \quad (16)$$

$$n \geq \frac{\cosh^{-1} \sqrt{\frac{10^{0.1 \cdot L_{AS}} - 1}{10^{0.1 \cdot L_{AR}} - 1}}}{\cosh^{-1} \Omega s} \quad (17)$$

The next step is to calculate the diameter and distance between the via walls, then determine the diameter and distance between the filter vias. After that, the ratio between the length and width of the taper is calculated. Finally, a 3-pole Chebyshev SIW filter based on the equation is shown in Figure 5 and the detailed parameter values are shown in Table 1.

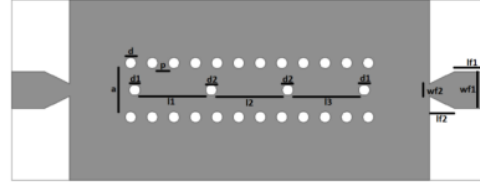


Figure 5. Filter Design.

TABLE 1. DIMENSIONS OF THE FILTER

No.	Name	Value (mm)
1	d	0.6
2	p	1.2
3	a	3.0014
4	d1	0.6
5	d2	0.6
6	l1 & l3	3.6449
7	l2	3.65
8	lf1	1.824930
9	wf1	2.043870
10	lf2	0.688445232
11	wf2	0.688445232

The simulation results of the filter performance at the center frequency of 24 GHz show the insertion loss of -4.0437dB, return loss -4.0820dB, VSWR of 4.337, and bandwidth of 256 MHz. These results did not meet the initial specifications. Therefore, an optimization step is carried out. Optimization by adding vias was carried out to obtain nearly ideal S_{11} & S_{22} parameters. Vias were added to guide the incoming waves from the feeder and taper through the area with the via filter, and thus minimize the unwanted scattered waves.

In addition, vias located at the very end of both sides of the filter close to the taper and feeder, are shifted by 0.8 mm to adjust the shape of the feeder and taper. The purpose is to guide the incoming waves directly. The optimized design results are shown in Figure 6 and the dimensional changes are shown in Table 3.

Figure 7 depicts the result of optimization where the S_{21} parameter or insertion loss value has a slight change but still meets the requirement value. At the 23.5 GHz frequency, which previously -0.7120 dB, the insertion loss decreases to -1.1086 dB, at the 24.5 GHz frequency, which previously -1.2473 dB, the S_{21} decreases to -1.2689 dB, while at the middle frequency which previously received S_{21} of -0.9124 dB, is now changes to -0.6695 dB. The lower stopband area was previously at 23.38 GHz, and after the optimization it has shifted slightly to 23.382 GHz. Meanwhile, the upper stopband, which was previously at 24.6320 GHz, has shifted to 24.6180 GHz. Moreover, the S_{11} or the return loss value has significantly changed but still meets the specification value and the resulting graphical shape is close to the ideal shape.



Figure 6. Optimization Result of the Filter Design.

TABLE 2. OPTIMATION PARAMETER

No.	Parameter	Value (mm)
1	d	0.6
2	p	1.2
3	a	2.4
4	d1	0.6
5	d2	0.8
6	l1 & l3	3.9473021532016
7	l2	3.5378823279004
8	lf1	10.039874138999
9	wf1	0.37783444116295
10	lf2	1.2341273596467
11	wf2	5
12	offsd1	0.48
13	offsd2	0.6

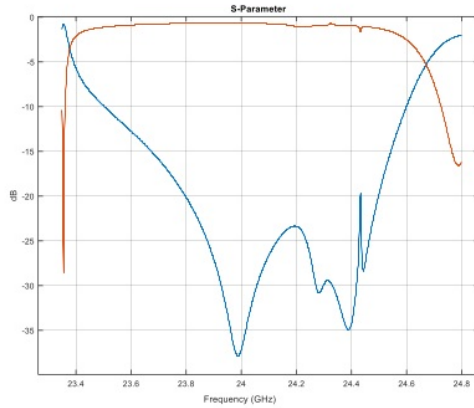


Figure 7. S-Parameter results.

At the 23.5 GHz frequency, the S_{11} changes from -16.9193 to -10.0260 dB, at 24.5 GHz frequency, the S_{11} changes from -16.2063 dB to -19.7888 dB while at the middle frequency, the S_{11} changes from -12.7049 dB to -36.9344 dB. In case of the stopband, the lower stopband is shifted from 23.424 GHz frequency to a frequency of 23.4690 GHz. Meanwhile, the upper stopband, which was previously at 24.6350 GHz, has shifted to 24.5990 GHz.

Figure 8 shows the VSWR value. There is a slight change but still meets the specification value. The VSWR at 23.5 GHz frequency was previously 1.3319, now is 1.9209, at the 24.5 GHz frequency, of the VSWR was previously 1.3602, now is 1.2283, while the VSWR at the middle frequency changes from 1.6028 to 1.0308. The lower stopband area, which was previously at 23.4190 GHz, has shifted to 23.4870 GHz. Meanwhile, the upper stopband, which was previously at 24.64 GHz, has shifted to 24.6060 GHz.

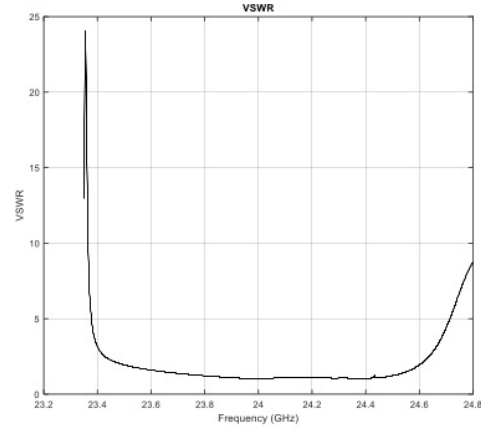


Figure 8. VSWR Result.

III. FABRICATION, MEASUREMENT, AND DISCUSSION

A. Fabrication

The proposed SIW filter is fabricated on RO4003C substrate with 0.813 mm thickness, as shown in Figure 9. The fabricated bandpass filter is measured using a microwave analyzer measuring instrument N9918A which has a measurement frequency range from 30 KHz to 26.5 GHz. The measurement is carried out to find out the technical data from the proposed filter design, namely insertion loss, return loss, and VSWR. The measurement results data then will be compared with the design specification data.

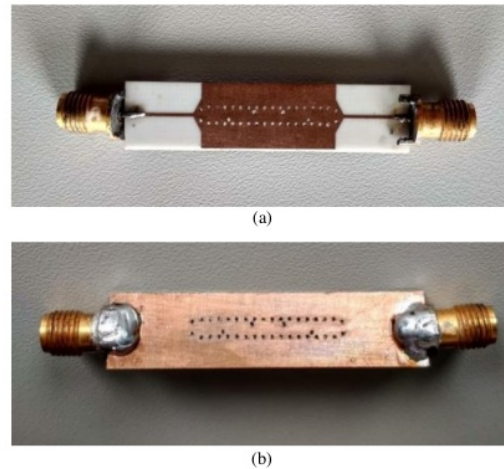


Figure 9. Fabricated Filter (a) Top View (b) Bottom View.

B. Measurement

Before starting a measurement, a calibration is carried out using a calibrator shown in Figure 10. In this step, it is found that there is a loss of -0.8109 dB that will affect the measurement results. This is marked with a red box in Figure 10.

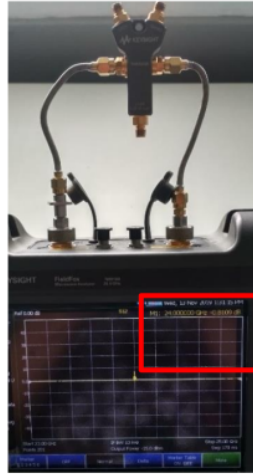


Figure 10. Measurement Calibration.

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C. Results and Discussion

Figure 11 shows the measurement results of the S_{21} or insertion loss parameter. Although there is a loss of -0.8109 dB from the measurement system, the device's performances still meet the pre-determined specification at 23.5 to 24.5 GHz. Considering the system loss, the S_{21} at 23.5 GHz frequency is -3.338 dB and at 24.5 GHz is -4.814 dB, while at 24 GHz is -4.316 dB. It is seen in the graph, there is a change in the measured bandwidth.

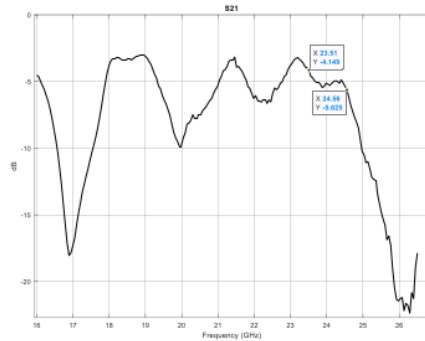


Figure 11. S_{21} Measurement Result.

Figure 12 shows the measurement results of the S_{11} parameter or return loss. In the frequency range of 23.5 to 24.5 GHz, the value obtained still meets the specification target when the result has been reduced by the loss of -0.8109 dB which was known from the previous calibration.

If the system loss is taken into account, the value of S_{11} at the 23.5 GHz frequency is -10.139 dB, at 24.5 GHz is -10.969 dB while at the 24 GHz frequency is -8.136 dB. Similar to the previous S_{21} measurement, there is a shift in the S_{11} of the bandpass section and it appears that the bandwidth is decreasing compared to the simulation.

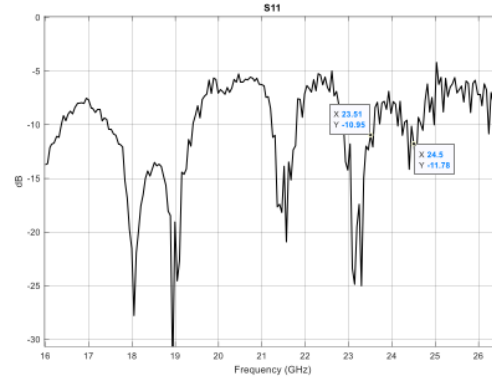


Figure 12. S_{11} Measurement Result.

Figure 13 shows a graph of VSWR measurement. The measured VSWR are 1.833 at 23.5 GHz, 1.649 at 24.5 GHz, and 2.067 at 24 GHz. Based on the overall measurement, all of the results at the frequency range of 23.5 to 24.5 GHz still meet the requirements that are specified earlier. It is noted, however, that the measurement results are far from ideal. The measured operation frequency is slightly shifted and the bandwidth is reduced compared to the simulation results.

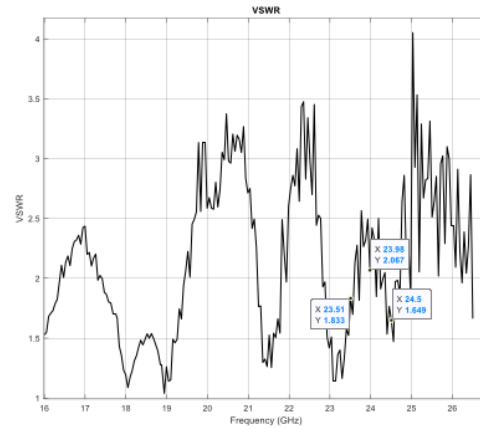


Figure 13. VSWR Measurement Result.

Based on the filter performance, although the insertion loss, return loss, and VSWR parameters still meet the initial specifications, there is a significant difference of the measured bandwidth parameter compared to the simulation. The summary of the performance results is shown in Table 3.

TABLE 3. SUMMARY OF PERFORMANCE RESULT

Parameter	Target	Simulation	Measurement
VSWR	≤ 2	1.0308	2.067
Insertion Loss	≥ -3 dB	-0.6695 dB	-4.316 dB
Return Loss	≤ -10 dB	-36.9344 dB	-8.136 dB
Bandwidth	1 GHz	1.236 GHz	580 MHz

The bandwidth discrepancy that occur during the measurement can be ascertained due to the fabrication factors. Based on the formula used when performing calculations, the diameter of the via filter and the distance between the via filters have an influence on the generated bandwidth. In addition, the dimensions of the taper also have a significant effect on the bandwidth and the value of other parameters, because this section is an adjustment between the feeder and the components of SIW.

Furthermore, the imperfect drilling process on the substrate in the SIW method also contributes to the result discrepancies. If the drilling process is done manually, there will be a possibility of size or placing inaccuracy that may affect the measured device's performances. In other words, a high precision fabrication is needed in the prototyping of the bandpass filter using the SIW method. In addition, fabrication losses may arise due to poor soldering of the connectors that can increase the attenuation of the filter.

CONCLUSION

12 We have designed and realized a bandpass filter using a substrate integrated waveguide structure. The design of the bandpass filter has a good agreement with the specification of short-range radar applications with a working frequency of 24 GHz. The realization of the bandpass filter gives good performances in terms of insertion loss, return loss and VSWR. Nevertheless, the bandwidth is reduced by about 50% compared with the simulation bandwidth. It is caused by the fabrication process such as hole drilling that requires precision. Furthermore, the change of the taper dimension during the fabrication also influence the bandwidth.

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