Design and Simulation of Microstrip Hairpin Bandpass Filter with Open Stub and Defected Ground Structure (DGS) at X-Band Frequency

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Abstract. In this paper we have designed and simulated a Band Pass Filter (BPF) at X-band frequency. This filter is designed for X-band weather radar application with 9500 MHz center frequency and bandwidth -3 dB is 120 MHz. The filter design was performed using a hairpin microstrip combined with an open stub and defected ground structure (DGS). The substrate used is Rogers RT5880 with a dielectric constant of 2.2 and a thickness of 1.575 mm. Based on the simulation results, it is found that the filter works on frequency 9.44 - 9.56 GHz with insertion loss value at pass band is -1.57 dB.

1. Introduction
The radar development has been increasingly rapid ever since the World War II. Radar is used as a supplement to war vessels and fighter planes for detecting enemy’s presence. Currently, radar system usage is broader, not only for military but also for commercial purposes such as for Air Traffic Control and weather or road monitoring.

One type of radar works at X-band frequency which is frequency range from 8 GHz to 12 GHz. X-band frequency is highly suitable for naval radar, airborne weather avoidance radar, airborne doppler navigation radar and police speed radar. Moreover, X-band frequency is also applied in marine radar, coastal surveillance radar, and weather radar.

Radar is a system consisting of three main components, namely antenna, transmitter and receiver. Receiver in a radar system has the capability of filtering the signal to make it suitable for detection as well as the capability of amplifying weak object signal and forwarding it to data and signal processor and then displaying it on the monitor screen [1]. Radar frequency is expected to work at 9-10 GHz, while X-band itself has frequency range of 8-12 GHz. With intervention in the frequency band due to wide spectrum of X-band frequency, filter is required to reject undesirable frequency.

Filter is an electronic circuit having a function of passing a desirable signal and/or not passing an undesirable signal [2]. Filter can be designed using many methods that have their respective advantages and disadvantages. These methods include hairpin, edge-coupled, parallel coupled, interdigital, and so forth. Hairpin has a relatively smaller size in comparison with other methods [3]. The selection of element order in hairpin method affects the dimensions and frequency response. The lower the number of element order (less than 5), the more sloping the frequency response and worse the selectivity. By contrast, the higher the number of filter element order (greater than 5), the steeper the frequency response and the bigger the filter dimensions [3].
In the research of hairpin microstrip bandpass filter, the addition of open stub in the first and last resonators may narrow the bandwidth to meet the desired specification [3]. Besides, to suppress the harmonics to increase the stop-band rejection without affecting the working frequency and insertion loss in bandpass filter, DGS (Defected Ground Structure) is added [4]. The selection of DGS may also increase the value of return loss [5].

The advancing development has increased the need for small, integrated passive component (filter). A component in large size physically will take larger space, thus attention should be put on minimizing filter dimensions to enable easy application of the filter.

In this research, filter is designed by using six order hairpin method and using open stub that can narrow the filter bandwidth as well as DGS to increase the stop-band rejection. The center frequency of this bandpass filter is 9.5 GHz. The simulation is carried out using 3D electromagnetic simulator software to figure out the performance of the filter by testing the necessary parameters.

2. Filter design

There are several key parameters used as a reference in BPF design. The specification of the BPF designed is expected to meet the parameters as shown in Table 1. The type of substrate used is Rogers RT5880. Table 2 shows the specification of the substrate Rogers RT5880.

| No. | Specification          | Values             |
|-----|------------------------|--------------------|
| 1.  | Working frequency      | 9.45 – 9.55 GHz    |
| 2.  | Bandwidth -3 dB        | 100 MHz            |
| 3.  | Centre frequency       | 9.5 GHz            |
| 4.  | FBW (Fractional BW)    | 0.01               |
| 5.  | Insertion loss         | > -2 dB            |
| 6.  | Return loss            | < -10 dB           |
| 7.  | Matching Impedance     | 50 ohms            |
| 8.  | VSWR                   | 1<VSWR<1.5         |
| 9.  | Filter poles           | 6                  |
| 10. | Frequency response     | Chebyshev          |

The initial stage of filter design is creating BPF using hairpin method with six resonators as shown in Figure 1. In the design of this bandpass filter, the dimensions of the filter should be obtained first. The dimensions of the filter calculated such as the width of resonator by using equations (1) and (2), the length of resonator by using equations (3) – (5), and the distance between resonators by using equations (6) and (7).

![Figure 1. Initial design of bandpass filter](image)

Table 2. Specification of the Substrate Rogers RT5880

| Specification          | Value   |
|------------------------|---------|
| Type of Substrate      | Rogers RT5880 |
| Dielectric Constant ($\varepsilon_r$) | 2.2 |
| Dielectric Loss Tangent ($\delta$) | 0.0009 |
| Thickness of Substrate (h) | 1.575 mm |

To find the width resonator line, the following equation is used:
\[
W = \frac{2}{\pi} \left\{ (B - 1) - \ln(2B - 1) + \frac{\varepsilon_r - 1}{2\varepsilon_r} \left[ \ln(B - 1) + 0.39 - \frac{0.61}{\varepsilon_r} \right] \right\} \tag{1}
\]
with
\[
B = 60\pi^2 \frac{Z_c \sqrt{\varepsilon_r}}{\varepsilon_r} \tag{2}
\]
thus,
\[
B = 60\pi^2 \frac{60\pi^2}{50\sqrt{2.2}} = 7.9825
\]
\[
W = \frac{2}{\pi} \left\{ (7.9825 - 1) - \ln(15.965 - 1) + \frac{2.2 - 1}{2(2.2)} \left[ \ln(7.9825 - 1) + 0.39 - \frac{0.61}{2.2} \right] \right\} = 3.08
\]
Since \( W/h > 2 \), the width of resonator line is obtained as follows:
\[
W = W_0 \times h = 3.08 \times 1.6 \text{ mm} = 4.9 \text{ mm}
\]
To obtain the length of resonator, equation (3) is used.
\[
L = \frac{\pi}{180^0} \theta^0 \text{ (in meter)} \tag{3}
\]
As hairpin bandpass filter uses a line of half of the wave length, \( \theta = 180^0 \), with
\[
\varepsilon_e = \frac{\varepsilon_{r+1} + \varepsilon_{r-1}}{2} \frac{1}{\sqrt{1 + 12 \left( \frac{h}{W} \right)}} \tag{4}
\]
\[
K_0 = \frac{2\pi f}{c} \tag{5}
\]
\( f \) is the center frequency of bandpass filter, while \( c \) is the speed of light in the air, with \( c = 3 \cdot 10^8 \text{ m/s} \).
Therefore,
\[
\varepsilon_e = \frac{2.2 + 1}{2} + \frac{2.2 - 1}{2} \sqrt{1 + 12 \left( \frac{1.6}{4.9} \right)} = 1.87
\]
\[
K_0 = \frac{2\pi \times (9.5) \times 10^9}{3 \times 10^8} = 198.96 \text{ m}^{-1}
\]
Thus, the length of hairpin resonator line (L) can be found by using equation (3).
\[
L = \frac{\pi}{180^0} \theta^0 = 180^0 m = 0.0115 m = 11.5 \text{ mm}
\]

The design of the filter is conducted by using low pass filter parameters based on Chebyshev table with ripple of 0.01 dB as the design parameter to get coupling coefficient [6] – [9]. It is used to determine the distance between hairpin resonator. Based on Chebyshev table, the six-order filter have the following parameters.

\[
g1 = 0.7814 \quad g2 = 1.3600
\]
\[
g3 = 1.6897 \quad g4 = 1.5350
\]
\[
g5 = 1.4970 \quad g6 = 0.7098
\]
\[
g7 = 0.9085
\]
By using the parameter values above, the coupling coefficient between resonators can be calculated using the following equations [7]:
\[
K_n = \frac{FBW}{\sqrt{g_n g_{n+1}}} \tag{6}
\]
\[ K = \frac{f_{H}^2 - f_{L}^2}{f_{H}^2 + f_{L}^2} \]  

(7)

As FBW is the fractional bandwidth of BPF, \( g_n \) is the low pass filter parameter based on the six order Chebyshev table. 

\[ K_n = \frac{FBW}{\sqrt{g_n \times g_{n+1}}} \]

\[ FBW = \frac{9500}{112.8} = 0.01 \]

\[ K_{12} = \sqrt{0.7814 \times 1.3600} = 0.0097 \]

\[ K_{23} = \sqrt{1.3600 \times 1.6897} = 0.0065 \]

\[ K_{34} = \sqrt{1.6897 \times 1.5350} = 0.0062 \]

\[ K_{45} = \sqrt{1.5350 \times 1.4970} = 0.0065 \]

\[ K_{56} = \sqrt{1.4970 \times 0.7098} = 0.0097 \]

\[ K_{67} = \sqrt{0.7098 \times 0.9085} = 0.0124 \]

\[ K_{12} = K_{56} \]

\[ K_{23} = K_{45} \]

After the coupling coefficient has been obtained, the next step is finding out the distance between resonators that matched with the coupling coefficient as calculated above. To find it, a simulation is carried out by observing S21 chart from the simulation results of cut-off frequencies, namely lower and upper cut-off frequencies.

The calculation conducted yields results: resonator width = 3.5 mm, resonator length = 4.7 mm and the distance between resonators = 1.2 mm. The next step is conducting simulation and optimization of the dimensions of the filter until the parameters of BPF match or near with the desired specification is obtained.

3. Initial Simulation

In this stage, the initial simulation of BPF is conducted, with results of dimensions obtained from literature study. The parameters of the filter without open stub and DGS can be seen in Table 3.

| Table 3. Filter Initial Parameters |
|-----------------------------------|
| **Parameters** | **Dimensions** |
| L              | 12 mm        |
| Lr             | 4.7 mm       |
| Lt             | 4 mm         |
| W              | 35 mm        |
| Wr             | 3.5 mm       |
| Wt             | 4.9 mm       |
| Wsr            | 0.7 mm       |

The simulation results do not show a good Band Pass Filter response shape, in which a considerable number of ripples are found, making the value of bandwidth unknown. Figure 2 and 3 show the initial design of the filter and results of the initial simulation based on calculation, respectively.
As the results of the initial simulation do not meet the expected specification, optimization is conducted by changing related parameters such as the distance between resonators (S), length of resonator (Lr), width of tap (Wt), DGS dimensions and length of open stub.

The results of the simulation based on the calculation do not show any suitable bandpass filter, so another simulation is conducted to obtain results meeting the specification. After conducting an analysis, this can be overcome by changing the distance between resonators 3 and 4 into zero mm, or in other words, the distance between resonators 3 and 4 is eliminated, and the sizes of the substrate and ground are also changed according to the reduction of distance between resonators 3 and 4. Figure 4 shows the design of change of distance between resonators 3 and 4, while Figure 5 shows the results of the simulation of parameter S from the change of distance between resonators 3 and 4. Optimization of distance between resonators can also shift the working frequency and change the bandwidth. The larger the distance between resonators, the higher the working frequency and the narrower the bandwidth, or vice versa.
Figure 6 shows that the shorter the length of the resonator, the higher the working frequency of the filter. On the other hand, the longer the length of the resonator, the lower the working frequency of the filter.

Table 4 shows the resulted difference after optimization is carried out on the length of tap. It is different in that the lower the width of tap, the higher the value of impedance.

![Figure 6. The effect of length of resonator line on working frequency](image)

| Table 4. Results of Optimization of Tap Width |
|----------------------------------------------|
| $W_t$ (mm) | Impedance (ohm) |
| 4.9        | 38.14          |
| 4.4        | 43.05          |
| 3.9        | 48.19          |
| 3.4        | 53.86          |
| 2.9        | 60.40          |

The results of the optimization of DGS are shown in Table 5, namely the return loss value of BPF with DGS is lower than the return loss of BPF without DGS. Figure 7 shows that the longer the open stub, the narrower the bandwidth, and vice versa.

![Figure 7. The effect of open stub length on bandwidth](image)

| Table 5. Comparison of S11 in the center frequency |
|-----------------------------------------------|
| BPF                                           |
| S11 (Return Loss) at Center Frequency         |
| Without DGS | -11.70 |
| With DGS   | -20.58 |

4. Results and discussion
After calculating the dimensions of the filter, and then some optimization is conducted on the dimensions of the bandpass filter, the dimensions of BPF meeting the desired specification are achieved. After the dimensions are optimized several times, the final dimensions of bandpass filter are obtained. Table 6
shows the change in dimensions after and before optimization. The final design of BPF for front and back views are shown in Figures 8 and 9, respectively.

### Table 6. Change in Dimensions Before & After Optimization

| Parameters | Dimensions Before Optimization | Dimensions After Optimization | Description |
|------------|---------------------------------|------------------------------|-------------|
| L          | 12 mm                           | 12 mm                        | Length of Substrate and Ground |
| L<sub>r</sub> | 4.7 mm                         | 5.23 mm                      | Length of Resonator Line |
| L<sub>t</sub> | 4 mm                           | 4 mm                         | Length of Tap |
| W          | 35 mm                           | 35.76 mm                     | Width of Substrate and Ground |
| W<sub>f</sub> | 3.5 mm                         | 3.5 mm                       | Width of Resonator |
| W<sub>t</sub> | 4.9 mm                         | 3.47 mm                      | Width of Tap |
| W<sub>r</sub> | 0.7 mm                         | 0.7 mm                       | Width of Resonator Line |
| h          | 1.6 mm                           | 1.6 mm                        | Thickness of Substrate |
| S<sub>f</sub> | 2.1 mm                         | 2.1 mm                        | Slide factor |
| s          | 1.2 mm                           | 1.69 mm                       | Distance between Resonators |
| L<sub>1</sub> | -                              | 7 mm                          | Length of DGS |
| L<sub>2</sub> | -                              | 0.5 mm                        | Length of DGS Line |
| W<sub>1</sub> | -                              | 0.7 mm                        | Width of DGS |
| W<sub>2</sub> | -                              | 0.5 mm                        | Width of DGS Line |
| S<sub>1</sub> | -                              | 0.5 mm                        | DGS Distance from SMA connector |
| L<sub>oss</sub> | -                              | 0.45 mm                       | Length of Open Stub |

After optimization is conducted on the distance between resonators (s), the length of resonator line (L<sub>r</sub>), width of tap, DGS size and length of open stub, the results of final simulation of bandpass filter are obtained as shown in Figure 10.

Figure 8. BPF final design, front view

Figure 9. BPF final design, back view

Figure 10. Final Bandpass Filter Simulation Results

Figure 10 shows the final results of bandpass filter simulation. From the simulation obtained that the return loss (S<sub>11</sub>) at the 9.5 GHz is -29.95 dB and the insertion loss (S<sub>21</sub>) is -1.57 dB. The BPF working frequency is 9.44 – 9.56 GHz, with bandwidth of 120 MHz. In addition to S<sub>11</sub> and S<sub>21</sub>, the VSWR at a
frequency of 9.5 GHz is also found that is 1.06. The results obtained are close to the specification determined in Table 1.

5. Conclusion
To obtain simulation results of parameter S in bandpass form, the distance between resonators 3 and 4 is changed into zero mm, thus eliminating the distance between resonators 3 and 4, or both resonators merged. To shift the working frequency of a bandpass filter, the length of the resonator line is changed. The longer the resonator line, the working frequency shift to the lower frequency. The use of open stub in the first and last resonators of BPF can narrow the bandwidth of the BPF designed. However, in addition to using open stub, narrowing the bandwidth can also be done by increasing the distance between resonators, except for the distance between resonators 3 and 4. The use of DGS may improve the value of return loss due to the difference in the value of return loss before and after the installation of DGS. The final results of bandpass filter simulation shown that filter parameters are close to the specification so that it can be used for x-band radar.

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