Design and realization of multi-section sum and diff 8 ways Wilkinson Power Divider at S-Band frequency for 3 dimensional radar application

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Abstract. The Wilkinson Power Divider (WPD) is one of the most common components used in array antenna feeding networks. It is lossless if the output ports are matched, reciprocal, and largely isolated. Many designs and modifications such as multi-section, open circuited stubs, or tapered transmission were proposed to increase the bandwidth of the conventional WPD. In this paper, we will discuss the design of multi-section sum and diff Wilkinson Power Divider for 3-dimensional radar application using CST Studio Suite 2018. The WPD operates at S-Band Frequency, realized in microstrip using substrate Rogers R0-4003C (lossy) with thickness 1.524 mm and relative permittivity 3.55. The simulation and measurement results are met the desired specification, which are less than -20 dB return loss, more than -10 dB insertion loss, less than -20 dB port isolation, and 180° phase difference.

1. Introduction

Radar, stands for radio detection and ranging, is an object detection system that uses radio waves to determine an object parameter such as distance, height, direction, and speed [1]. The important part of the radar system is a transmitter (Tx) that connected to an antenna and sends electromagnetic waves towards the target, and a receiver (Rx) that connected to a receiving antenna and receive all the reflected waves from the radar target. Three-dimensional radar tracking is the development of two-dimensional radar tracking. Two-dimensional radar tracking only covers distance and angular direction, whereas three-dimensional radar tracking includes distance, angular direction, and height. Antennas are an important part of a radar system. Antennas used in radar systems usually have a better direction, where the main and null lobes can be adjusted in direction. This antenna can be realized by arranging some antenna elements into certain settings called arrays antenna. To supply power to the array antenna, a power divider is needed. Power dividers can be either a power divider or a power combiner. Power divider is one of the passive microwave components which can divide one input signal to two or more output signals [2].

The Wilkinson Power Divider (WPD) is a basically a three-port network that is lossless when all output ports are matched. Input power can be divided into two or more with the same amplitude, for two ways WPD using λ/4 impedance transformation [3]. In general, this WPD is considered a microstrip lines as shown in figure 1.
Figure 1 is the simplest WPD consisting of two transmission line with a quarter wavelength channel. The WPD characteristic impedance (Z0) is 50 ohms and the resistor impedance is 2Z0 [3]. Cohn introduced WPD multi sections to widen the bandwidth of conventional WPD [4]. After that, there was a lot of research studies about WPD multi-section, some of the research results have disadvantages, namely increasing in insertion loss value and larger dimensions although it still provides a good isolation between the output ports and larger bandwidth [5]. Recently, many studies have addressed the design of the WPD multi-section [6-10]. In this paper, we will design a Wilkinson Power Divider 1x8 multi-section sum and diff working on the S-Band frequency, with frequency range 2.9–3.1 GHz. To realize the design, we first designed the 1x2 WPD then 1x4 WPD until it was developed up to 1x8 WPD. Sum and diff are part of the monopulse tracking system. Monopulse which is also known as simultaneous lobe comparison (simultaneous beams), is a technique for determining the angular location of a radar target or radiating source. This technique can eliminate errors caused by fluctuations in the target's echo amplitude and increase the data bit rate, because the angular information can be divided into two equal lobe angles [11-14].

2. Research methods
This research was carried out through four stages namely design, simulation, fabrication, and measurement. WPD is designed using CST Studio Suite 2018 software based on reference designs. In the simulation stage, optimization is done several times to get the desired specifications. After the optimal design is obtained, fabrication and measurement of return loss, insertion loss, port isolation and phase difference parameters are carried out. Each stage of the study was carried out through the flowchart as shown in figure 2.
3. Results and discussion

This section describes the three stages of research, namely design, simulation and fabrication of the multisection sum and diff 1x8 Wilkinson power divider. The design stage is to determine the WPD specifications such as geometry shapes, operating frequency, return loss, insertion loss, and isolation port. The simulation stages are to find out the optimal result. After the optimal design is obtained, the fabrication and measurement are carried out.

3.1. WPD design

The WPD is designed using the Rogers RO-4003 C (lossy) as a substrate which has the specifications are listed in table 1, while the desired specifications are listed in table 2. To begin the design of WPD multisection, we first determine the characteristic impedance and resistor values for each section [4]. A theoretical calculation is done to find out the width and length of the line. Table 3 is a calculation of the dimensions of multi-section sum and diff WPD.

| Substrate Type                  | Rogers RO-4003C (Lossy) |
|---------------------------------|--------------------------|
| Relative permittivity (ε_r)     | 3.55                     |
| Tangent Loss (tan δ)            | 0.0027                   |
| Thickness                       | 1.524 mm                 |

| Parameter                      | Value                     |
|--------------------------------|---------------------------|
| Return Loss Sum and Diff       | ≤ -15 dB                 |
| Insertion Loss Sum and Diff    | ≥ -10 dB                 |
| Isolation Port                 | ≤ -20 dB                 |
| Diff Phase                     | 180°, ± 2.5°             |

3.2. Simulation results

Using the calculation results, simulation process is carried out using CST Studio Suite 2018 to met the desired specifications. The simulation is carried out several times by changing the dimensions and parameters of WPD so that optimal results are obtained. Calculated resistor value of both WPD are $R_1=602.486 \, \Omega$, $R_2=92.356 \, \Omega$, and $R_3=93.367 \, \Omega$. Because this resistor value is not available in the market, we use 100 Ω resistor instead of 92.456 Ω and 93.367 Ω, and 620 Ω resistor instead of 602.486 Ω during simulation and fabrication. The selected resistor value is slightly higher to increase isolation between ports [6]. Without using a resistor, high isolation value between the output ports will not provide [15].

| Dimension                      | Formula and Results |
|--------------------------------|---------------------|
| Impedance (Z) and resistor     | To get a value of   |
| value (R) each sections        | impedance and resistor value use Paper Cohn |
|                                | Equation’s [4],     |
|                                | Impedance and resistor value are, |
|                                | $Z_1=54.25 \, \Omega$, $R_1=602.486 \, \Omega$ |
|                                | $Z_2=70.71 \, \Omega$, $R_2=92.356 \, \Omega$ |
|                                | $Z_3=91.70 \, \Omega$, $R_3=93.367 \, \Omega$ |
Table 3. Cont.

| Dimension             | Formula and Results                                                                 |
|-----------------------|--------------------------------------------------------------------------------------|
| Width of Transmission lines (W) | To get value of B use equation [2], 
  \[
  B = \frac{377\pi}{2Z_0\sqrt{\varepsilon}}
  \]  
  And to get value of W use equation [2],  
  \[
  W = \frac{2}{\pi} \left[ B - 1 - \frac{\varepsilon}{2\varepsilon_i} \left( \ln(B - 1) + 0.39 - \frac{0.61}{\varepsilon_i} \right) \right]
  \]
  width for each section is,  
  \[
  W_{Z1} = 1.066 \text{ mm}; W_{Z2} = 1.859 \text{ mm} \\
  W_{Z3} = 2.958 \text{ mm}; W_{Z0} = 3.400 \text{ mm}
  \]  
  \[\varepsilon_{\text{eff}}\] To get the value \(\varepsilon_{\text{eff}}\) use equation below. In this case the value of \(W_{\text{eff}}/h \geq 1\) then  
  \[
  \varepsilon_{\text{eff}} = \frac{1}{2} + \frac{\varepsilon_i - 1}{2} \left( 1 + 12 \left( \frac{h}{w} \right) \right)^{0.5}
  \]  
| Length of transmission lines (L) | To get the value length for each section use equation [2],  
  \[
  \lambda_c = \frac{\lambda_0}{\sqrt{\varepsilon}}
  \]
  \[
  L = \frac{\lambda_c}{4}
  \]
  length for each section is,  
  \[
  L_{Z1} = 15.581 \text{ mm}; L_{Z2} = 15.321 \text{ mm} \\
  L_{Z3} = 15.064 \text{ mm}; L_{Z0} = 14.992 \text{ mm}
  \]  
  For diff,  
  \[
  L_{Z0 \text{diff}} = 44.976 \text{ mm}
  \]  
| Metered Bend (X) | To get the value X for each section use [2],  
  \[
  D = w\sqrt{2}
  \]
  \[
  X = D(0.52 + 0.65e^{-1.35(\frac{h}{w})})
  \]
  \[
  A = (X - D/2)\sqrt{2}
  \]
  Metered bend for each section is,  
  \[
  X_{Z1} = 1.164 \text{ mm}; X_{Z2} = 1.696 \text{ mm} \\
  X_{Z3} = 2.373 \text{ mm}; X_{Z0} = 2.653 \text{ mm}
  \]
  With value of A for each section is,  
  \[
  A_{Z1} = 0.580 \text{ mm}; A_{Z2} = 0.536 \text{ mm} \\
  A_{Z3} = 0.393 \text{ mm}; A_{Z0} = 0.352 \text{ mm}
  \]  

In designing WPD, we first designs WPD sum 2 ways, 4 ways, up to 8 ways. The final 3 sections WPD 8 ways shown in Figure 3, and it will be fabricated with the optimization dimensions listed in table 4. After designing the WPD sum, we then designed 3 section diff WPD 8 ways by adding \(\lambda/2\) to one of the \(Z_0\) line lengths shown in figure 4.
Table 4. Final parameter of 3 section Sum and Diff WPD.

| Parameter                        | Dimension Value                  |
|----------------------------------|----------------------------------|
| Length of Substrate              | 179 mm                           |
| Width of Substrate               | 56.5 mm                          |
| Impedance (Z) and Resistor Value (R) | \( Z_1 = 54.25 \, \Omega, \, R_1 = 620 \, \Omega \) |
|                                  | \( Z_2 = 70.71 \, \Omega, \, R_2 = 100 \, \Omega \) |
|                                  | \( Z_3 = 91.70 \, \Omega, \, R_3 = 100 \, \Omega \) |
| Width of Transmission Line (W)   | \( W_{z3} = 1.066 \, \text{mm}; \, W_{z2} = 1.859 \, \text{mm} \) |
|                                  | \( W_{z1} = 2.550 \, \text{mm}; \, W_{z0} = 3.400 \, \text{mm} \) |
| Length of Transmission Line (L)  | \( L_{z3} = 16.418 \, \text{mm}; \, L_{z2} = 16.40 \, \text{mm} \) |
|                                  | \( L_{z1} = 15.728 \, \text{mm}; \, L_{z0} = 54.62 \, \text{mm} \) |
|                                  | \( L_{z0 \, \text{diff}} = 45 \, \text{mm} \) |
| Metered Bend (X)                 | \( X_{z3} = 1.164 \, \text{mm}; \, X_{z2} = 1.696 \, \text{mm} \) |
|                                  | \( X_{z1} = 2.274 \, \text{mm}; \, X_{z0} = 3.500 \, \text{mm} \) |
|                                  | With value of A for each section is, |
|                                  | \( A_{z3} = 0.580 \, \text{mm}; \, A_{z2} = 0.539 \, \text{mm} \) |
|                                  | \( A_{z1} = 0.416 \, \text{mm}; \, A_{z0} = 0.352 \, \text{mm} \) |

Figure 3. Model of 3 sections sum 8 ways WPD.

Figure 4. Model of 3 sections diff 8 ways WPD.

Figures 5 and 6 show the overall parameters of the simulation results for ports S11 through S99. The return loss has a value of less than -20 dB at a frequency of 3 GHz. Figures 9 and 10 show the isolation parameters of adjacent output ports such as S23, and S29 distant ports with values smaller than -20 dB. Figure 11 shows the different phase parameters in the WPD diff, where the results of S21, S31, S41, S51 are almost 180° different with S61, S71, S81, S91. Thus WPD are met the desired specifications, even though it is not exactly 180°, but when it is simulated with an antenna, the radiation pattern results are as expected.
Figure 5. Return loss of sum 8 ways WPD.

Figure 6. Return loss of diff 8 ways WPD.

Figure 7. Insertion loss of sum 8 ways WPD.

Figure 8. Insertion loss of diff 8 ways WPD.

Figure 9. Port isolation of sum 8 ways WPD.

Figure 10. Port isolation of diff 8 ways WPD.
3.3. Realization

The WPD realization of the 3 section sum and diff 8 ways printed on the Rogers RO-4003 C (lossy) substrate, with the SMA connector and the resistor value used according to the simulation. Fabrication results of 3 section sum and diff 8 ways respectively as shown in figures 12 and 13.

![Fabrication of sum WPD](image12.png)

**Figure 12.** Fabrication of sum WPD.

![Fabrication of diff WPD](image13.png)

**Figure 13.** Fabrication of diff WPD.

The next step, the measurements results are compared with the simulation results. All parameters have been measured using the Vector Network Analyzer (VNA). Figures 14-19 show the comparison graph.
of simulation and measurement result. Figure 14 and 15 show the return loss parameters, which are less than -20 dB at a frequency of 2.9 GHz-3.1 GHz. Figures 16 and 17 show the port isolation parameters, which are smaller than -20 dB at a frequency of 2.9 GHz-3.1 GHz. Figure 18 and 19 show the insertion loss parameter. Ideally when the power divider is given input power of 0 dBm, then the eight output ports have a power of -9 dBm. The measurement and simulation results show that the output varies from -9 dB to -10 dBm for each output port at each sample frequency, meaning this still meets the desired specifications. Figure 19 shows 180° phase difference between S21 and S61 ports for the simulation results and 182° phase difference for measurement result.

![Figure 14. Graph comparison between return loss results of simulation and measurement Sum WPD.](image14)

![Figure 15. Graph comparison between return loss results of simulation and measurement Diff WPD.](image15)

![Figure 16. Graph comparison between port isolation results of simulation and measurement Sum WPD.](image16)

![Figure 17. Graph comparison between port isolation results of simulation and measurement Diff WPD.](image17)
4. Conclusion

The multisection sum and diff WPD for 3 dimensional radar applications has been designed and fabricated. The specification for the WPD at frequency 2.9 – 3.1 GHz has been achieved with the value of Return loss less than -15 dB, Insertion loss more than -10 dB, Port isolation less than -20 dB and Phase difference for diff WPD have acceptable and amplitude imbalance less than (± 2.5º).

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