Design and analysis of a compact Wilkinson Power Divider with Harmonic Suppression

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Abstract— The Wilkinson Power Divider is used to split the input power equally or unequally between two output ports, ideally without loss. One of the main drawbacks of the Wilkinson Power Divider is a narrow bandwidth and this can be improved by adding a quarter-wavelength section in front of the power divider/combiner. In wireless applications, this affects the performance of the system drastically. In this paper, the Conventional Wilkinson power divider and the Compact Reversible harmonic suppressed Wilkinson power divider is proposed. The Power divider is simulated on FR4 dielectric substrate using a simulation tool Agilent advanced design system (ADS) 2013. The proposed power divider is analyzed and it provides compactness, low insertion loss, better isolation between the output ports and harmonic suppression characteristics.

Keywords—Compactness; Harmonic suppression; Wilkinson power divider(WPD); ADS

I. INTRODUCTION

The Wilkinson Power Divider was introduced by Ernest J. Wilkinson in 1960[1]. It can also be used in the reverse direction as a power combiner. Other properties of the Wilkinson power divider is that all ports are matched, the two output terminals are isolated from one another, and that it is reciprocal. Reciprocal means that you get the same result if you send the signal from one port to another in either direction. Three-port networks cannot be reciprocal and matched without being lossy. The solution to this, in the Wilkinson Power Divider, is to add a resistor between the two outputs. This resistor absorbs energy if there is any mismatch between the output ports. It also helps to isolate the two outputs when the circuit functions as a power combiner. It finds practical applications in antenna sharing, test labs and in-building networks. It is used for a wide range of communication signals like GSM, PCS, WCDMA, and UMTS.

In the past, the suppression of harmonic bands is usually attained by adding separate filter modules. In the last decade, this problem has been partially overcome by using defected ground structure (DGS) or electromagnetic bandgap (EBG) cells for the suppression of one or two harmonic frequency bands. Unfortunately, these circuits usually require either backside etching or additional lumped reactive element, which is undesirable for low cost and mass production environment. Moreover, explicit design formulas are often not available and the desired responses are mainly obtained by computer optimization. Power dividers are the indispensable part of many sophisticated blocks such as Doherty power amplifier, phased array antennas, I/Q vector modulators, balanced mixer and frequency multipliers. Rapid developments in the field of multiband/ multi-standard wireless communication systems have profound impact on how the state-of-the-art circuits and systems are developed and designed. Radio frequency (RF) systems (i.e. radio or television) with multiple channels commonly use the Wilkinson Power Divider because the output ports are well isolated, and thus prevent crosstalk.

The main objective of this work is on realizing wideband design, miniaturization[2][4] and achieving additional filtering and harmonic suppression[6][8][9]. It aims at the rigorous formulation and analysis based on transmission line theory [3], which is carefully verified with ADS circuit models and Electromagnetic (EM) Simulation. Designs are implemented on micro strip lines for low-cost, ease of fabrication and compatibility. In Section II, the design and analysis of the conventional power divider and the different structures of harmonic suppressed compact power dividers are given which provides better insertion loss, return loss characteristics along with good isolation between the output ports is also achieved. Since Insertion loss refers to the additional loss above the nominal loss due to splitting, they are the main consideration for suppression of harmonics. A Wilkinson power divider, on the other hand, can achieve isolations better than 20 dB since a common engineering trade-off tends to exist in power dividers that the larger the bandwidth and the higher the frequency, the more difficult it is to provide good isolation. In Section III Electromagnetic (EM) simulations are discussed and they carried out using a simulation tool ADS. The parameters like Insertion loss, Return loss, isolation, and size are compared. In Section IV Conclusion about the different structures of
simulated Wilkinson power dividers along with the pros and cons are outlined.

II. DESIGN AND ANALYSIS

A) The conventional Wilkinson design is simple and efficient, but it has a limited band of operation. Schematic of an equal split two way conventional WPD is depicted in Fig.2.1. It comprises of two quarter wavelength transmission lines each having a characteristic impedance of $\sqrt{2}Z_0$ and an isolation resistor $R = 2Z_0$. The schematic drawn in ADS is shown in Fig.2.2 where for a 50 Ω impedance 100 Ω isolation resistor is used.

\[ Z_o = \frac{Z_f}{(1 + \varepsilon_{eff} \left[ \frac{w}{h} + \frac{2}{3} \ln \frac{w}{h} + 1.444 \right])} \]

where

\[ \varepsilon_{eff} = \frac{\varepsilon_r + 1}{2} + \frac{\varepsilon_r - 1}{2} \left[ 1 + \frac{12h^{-1/2}}{w} \right] \]

Fig. 2.1 Conventional Wilkinson power divider (WPD) using transmission lines.

Fig.2.2. Schematic of an conventional Wilkinson power divider

B) For achieving harmonic suppression characteristics a 2.45-GHz WPD with frequency selecting coupling structure [9] is employed with the leading transmission lines and dielectric constant of 2.54 and a thickness of 0.54 mm is chosen. The designed layout of harmonic suppression component is given in Fig.2.3 where the width and length calculations are done using a tool called line calc in ADS. It is having a compact size of 7.74 mm ×18.64 mm corresponding to 0.10λg × 0.24λg with both the ports impedances are set to be 70.7Ω as follows from the design equations (1) and (2).

Fig.2.3 Layout of harmonic suppression component

The port impedances of the circuit can be derived from the following equation of finding $Z_o$:

Additionally, short-circuited stubs are shunt connected at the end of the two output ports with the isolation resistor of 100Ω. It has an electrical length of $\pi/2$ based on the operating frequency. It can block the dc and low-frequency components, in the operating frequency band. The bandwidth of the WPD can be tuned by the dimensions of the stub, in which the width affects the quality factor (Q) and the length affects the transmission zero in the operating band, respectively, thereby wideband characteristics can also be attained further by trial and error. Then the structure is simulated in the schematic.
window of ADS and the results includes return loss (denoted as S11), Insertion loss (denoted as S21, S31) for both the ports 2 and 3, Isolation (denoted as S32) parameter, gain and directivity.

C) Another method of the miniaturization of the power divider is realized with Open circuited stub [4], which acts as a capacitive loading is shown in below Fig. 2.4. The substrate specifications are FR4 dielectric substrate with permittivity of 4.5, height of 1.5mm is used. The divider also suppress the higher order harmonics thereby acting as low pass filter by providing insertion loss (S21 & S31) characteristics better than -30dB.

The overall size of this power divider is 8.95 mm x 16.94 mm corresponding to 0.15 λg x 0.28 λg where λg is the guided wavelength. The comparison is made with all the S-parameters like insertion loss, return loss and isolation between the output ports.

D) One more method of achieving wide band is by means of a reversible power divider by using rectangular rings of different impedances on microstrip line that fit within Wilkinson power divider. The term reversible means that front and back side of power divider is similar and it is the big advantage of the design which is shown in Fig. 2 & 3 of [7]. In order to achieve the wide bandwidth the divider is established by using these rectangular rings and etching a slot on widest rectangular section of divider as shown in Fig. 2.5. In the design results indicate that proposed power divider has wide bandwidth, compact size, reversible structure, good impedance matching and low insertion loss. The substrate with dielectric constant of 9 and thickness of 0.8 mm is used and isolator resistor R = 100 ohm enhances the isolation between output ports and used to avoid mismatch between the output ports.

\[ \cot \beta l = 1/(Z_0\omega) \]  

For a design frequency of 9.2 GHz and ports impedance of 50 ohm, the design area is 15 mm x 5.6 mm. Another advantage of using rectangular shaped divider is that all output ports are designed together. Further the simulation results are discussed in Section III.
III. RESULTS AND DISCUSSION

(B) The proposed power dividers are simulated using a software Advanced design system (ADS). The simulated S parameter results of harmonic suppression component [9] are shown in the following figures Fig.3.1 & Fig.3.2. The Fig.3.1 shows that the power is equally divided between the ports 2 & 3. The measured −20 dB bandwidth is from 2.45 to 6.78 GHz, with insertion losses S21 and S31 above −5 dB in the operating frequency. Other than the operating frequency f0, the insertion loss of -38dB is incurred as the minimum. The phase difference of port 2 and port 3 is only 1° which indicates that the power is also equally divided in phase. The small deviation could be due to losses and discontinuities. The 3f0, 5f0, and 7f0 components are all suppressed well. The isolation between port 2 and port 3 (S32) is −10 dB at 2.45 GHz and -37dB at f=13.8GHz shown in the Fig.3.2.

![Fig.3.1 Simulated insertion loss (S21&S31)characteristics](image1)

![Fig.3.2. Isolation characteristics](image2)

(C) The simulated insertion loss results of miniaturized Wilkinson power divider [4] is shown in Fig.3.3. From graph, it is clear that higher order harmonics are suppressed by offering S21 better than -30 dB. At f=6.6GHz it offers the lowest insertion loss of -55dB and it is nearer to the third harmonic frequency. Hence, it is clear that higher harmonics are suppressed showing it offers high attenuation. Measured bandwidth is defined as the frequency band for which abs (S11) is < -15 dB and % BW utilization is shown in Fig.3.4. It shows that it can be used for S band (2-4GHz) applications. It also gives the high isolation between the output ports better than -30 dB as shown in Fig.3.5. The measured S11,S21,S31 and S32 at the operating frequency 2.4GHz are -9.1dB,-3.5dB,-3.5dB,-3.4dB respectively. The return loss decays up to -23dB at f=3.4GHz.

![Fig.3.3 Simulated S21 and S31](image3)

![Fig.3.4. Simulated results of return loss Vs frequency](image4)
(D) The simulated return loss characteristics of compact reversible Wilkinson power divider is shown in Fig.3.6. It shows that the magnitude of $S_{11}$ is $-8\text{dB}$ at $f=9.2\text{GHz}$ and $-19\text{dB}$ at $f=4.5\text{GHz}$ and also return loss become less than $-10\text{ dB}$ over entire UWB range. It has been seen from the Fig.3.7 and Fig.3.8 that the input power has been splitted equally in both magnitude and phase between two output ports. There is only a very slight difference exists. This also shows that the transmission parameter $S_{21}$ and $S_{31}$ are very close to $3\text{dB}$ at the desired frequency range covering L band(1-2GHz), S band (2-4GHz) and UWB(3.1-10.6GHz) range. Fig.3.9 shows the isolation results of ports 2 and 3. It provides the isolation of $-3\text{ dB}$ at the designed operating frequency. The measured $S_{11},S_{21},S_{31}$ and $S_{32}$ at the operating frequency $9.2\text{GHz}$ are $-7.7\text{dB}$, $-5\text{dB}$, $-8\text{dB}$ respectively.

![Fig.3.5 Simulated results of miniaturised wilkinson power divider for isolation characteristics](image)

![Fig.3.6 Simulated results of return loss (S11)](image)

![Fig.3.7 Simulated results of insertion loss Vs frequency](image)

The comparative study of different Wilkinson power dividers are made based on the parameters like Insertion loss, Return loss and Isolation with both the operating frequency and at the frequency at which the minimum loss is obtained which is shown in below Table.1. The size comparison is also made for each structure with respect to guided wavelength.

<table>
<thead>
<tr>
<th>Structure</th>
<th>Operating frequency (GHz)</th>
<th>Insertion loss $S_{21},S_{31}$ (dB)</th>
<th>Return loss $S_{11}$ (dB)</th>
<th>Isolation $S_{32}$ (dB)</th>
<th>Size $(\text{mm} \times \text{mm})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(A)</td>
<td>915MHz</td>
<td>-3,-3</td>
<td>-55.19</td>
<td>-59.40</td>
<td>7.72 x 44.9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$(0.049 \lambda_g \times 0.28\lambda_g)$</td>
</tr>
<tr>
<td>(B)</td>
<td>2.45GHz</td>
<td>-12,-12</td>
<td>-1.3</td>
<td>-4</td>
<td>7.74 x 18.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$(0.10 \lambda_g \times 0.24\lambda_g)$</td>
</tr>
<tr>
<td></td>
<td>Other than $f_0$</td>
<td>-38,-38</td>
<td>-11 at $f = 5$</td>
<td>-37 at $f = 13.8$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$f = 2.8$</td>
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<td></td>
<td></td>
<td></td>
<td>$f = 3f_0$</td>
</tr>
<tr>
<td>(C)</td>
<td>2.4GHz</td>
<td>-5,-5</td>
<td>-9</td>
<td>-5</td>
<td>8.95 x 16.94</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$(0.15 \lambda_g \times 0.28\lambda_g)$</td>
</tr>
<tr>
<td></td>
<td>Other than $f_0$</td>
<td>-55,-55</td>
<td>-23 at $f = 3.3$</td>
<td>-36 at $f = 3f_0$</td>
<td></td>
</tr>
<tr>
<td></td>
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<td>$f = 2.8$</td>
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<td></td>
<td></td>
<td></td>
<td>$f = 3f_0$</td>
</tr>
<tr>
<td>(D)</td>
<td>9.2GHz</td>
<td>-5,-5</td>
<td>-8</td>
<td>-3</td>
<td>15 x 5.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$(0.68 \lambda_g \times 0.24\lambda_g)$</td>
</tr>
<tr>
<td></td>
<td>-6.5 at $f = 12$</td>
<td>-19 at $f = 4.5$</td>
<td>-13 at $f = 12$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
provides return loss better than -10 dB, a nominal value. Higher isolation value between the output ports is also achieved as -6 dB. Finally, a compact reversible power divider of rectangular rings on microstrip line with a slot etched on widest rectangular section is analyzed for various L band, S band and UWB applications. It provides the compact size of 15 mm × 5.6 mm with the return loss better than -10 dB at the UWB band. From the simulation results, good isolation has been obtained.

![Fig.3.8 Simulated phase plot of S21 and S31](image)

![Fig.3.9 Simulated results of isolation Vs frequency](image)

IV. CONCLUSION

A 2.45-GHz WPD with frequency selecting coupling structure provides a very compact size of 0.10λg × 0.24λg as well the equal splitting of power both in magnitude and phase with insertion losses S21 and S31 above −5 dB in the operating frequency. The dc component, 3 f0, 5 f0, and 7 f0 harmonic components are suppressed well. Secondly, Wilkinson power divider with the capacitive loading through open stub is analyzed which gives us the miniaturization in the structure and with the very low insertion loss of -55dB at the third harmonic frequency. The results show that the divider provides return loss better than -10 dB, a nominal value. Higher isolation value between the output ports is also achieved as -6 dB. Finally, a compact reversible power divider of rectangular rings on microstrip line with a slot etched on widest rectangular section is analyzed for various L band, S band and UWB applications. It provides the compact size of 15 mm × 5.6 mm with the return loss better than -10 dB at the UWB band. From the simulation results, good isolation has been obtained.

References