A Miniaturized Wilkinson Power Divider for Ultra Wide-band Operation

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Abstract— **This paper presents a new miniaturized multi-section Wilkinson power divider based on coupled-line for ultra-wideband operation. The proposed divider is composed of three-sections. An even- and odd-mode analysis is used to calculate the characteristics impedances at the designed frequency, and the performance is optimized for ultra-wideband operation from 0.9 to 4.1 GHz. The realized power divider has return loss lower than -10 dB and insertion loss better than -3.8 dB for the frequency band 0.9-4.1 GHz. Moreover, it occupies more than 60% smaller circuit area compared to conventional ring structure Wilkinson power divider. The measurement results show the good agreement with simulated ones.**

Index Terms—**Coupled-lines; miniaturization; ultra-wideband; Wilkinson power divider.**

I. INTRODUCTION

In order to satisfy the growing demand of wireless communication system various type of microwave Wilkinson power dividers (WPDs) have been investigated for antenna feeding networks and for microwave amplifiers [1]-[4]. The conventional ring structured Wilkinson power divider provides very good input and output port matching, high isolation, and low insertion loss. However, conventional power dividers are quite large in size and with limited operational bandwidth, especially in L- and S-Band, where the quarter-wave transmissions lines can be several centimeters long [1]. Because of this reason, they are not applicable in many ultra-wideband communication systems. Therefore, techniques to minimize the occupied area and enhance the operational bandwidth of power dividers are interesting for low cost and small size circuits.

There are many ways to improve the operational bandwidth and reduce the circuit size of a power divider [3]–[7]. The most widely adopted technique to improve bandwidth is adopting a multi-section structure [4]–[8], with more than 100% fractional bandwidth (FBW) achievable. However, multi-section structures occupy large circuit area. The power divider presented in [1] not only has a compact structure with 50% reduced the circuit size compared to conventional design, but also provides more design freedom. However, the smaller bandwidth limits its applications. Another technique to reduce the circuit size of a power divider was discussed in [2]. There, quarter-wave transmission lines are reduced using capacitive loading technique and correspondingly increasing the transmission line characteristic impedance but at the expense of bandwidth reduction.

Even though, there have been several studies that revealed improvement in insertion- and return-loss bandwidth or reduction in the occupied area of WPDs, but no design presents circuit size reduction with wideband operation improvement simultaneously.

In this paper, an ultra-wideband two-way Wilkinson power divider with reduced size is presented. This circuit has three-section coupled-lines and three isolation resistors. The divider circuit is based on closely spaced coupled-lines. Consequently, it is very convenient to place isolation resistors between coupled-lines. This also means that the size of practical layout can be very small, leading to a miniaturized power divider. The design of the proposed power divider is based on even- and odd-mode analysis. The proposed divider not only effectively reduces the occupied area more than 60% compared to conventional ring structured WPD at 3.5 GHz. It also presented good performances for ultra-wideband from 0.9 to 4.1 GHz. The measured maximum insertion loss over the ultra-wideband is -3.8 dB only.

II. WIDEBAND WILKINSON DIVIDERE

The conventional power divider has wider adaptability in microwave application due to its simple structure. However, limited operational bandwidth turns out to be an obstruction for adaptability of single-stage power divider. Fig. 1 depicts the proposed 3-section WPD and its parameters implemented by using the uniform microstrip parallel coupled-lines and three isolation resisters. The parameters Z_{ie}, Z_{io} and Θ represent the even-, odd-mode impedances and electrical length of each coupled-section lines, respectively. The Z_0 represents the impedance terminating the input and output ports.

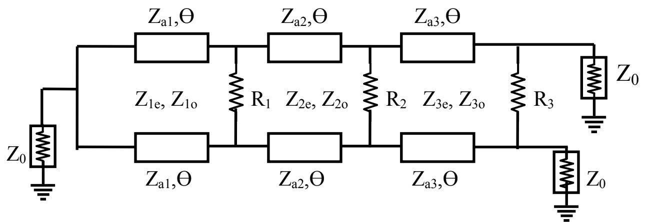

Fig. 1. Proposed three-section coupled-lines Wilkinson power divider.

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The design goal is to determine the optimum values of characteristics impedances of even- and odd-mode for each section of the power divider to minimize the insertion losses and keep adequate reflections at all ports for the desired bandwidth. It can be seen from Fig. 1 that the final performances of the power divider mainly depend upon on three groups of parameters, which are electrical length (θ_i), characteristics impedance (Z_i) and isolation resistors (R_i), where i = 1,2, and 3. It is demonstrated in [2] that it is possible to reduce the coupled line length from λ /4 to λ /12, but at the cost of isolation and output return losses bandwidth reduction. Therefore λ/8 transmission line is selected for all three sections by taking into account the reduction in insertion- and return-loss bandwidth. Fig. 2 shows the simplified form of proposed power divider by using the even-odd mode analysis technique. The influence of the even- and odd-mode impedances on S-parameters is presented in [1].

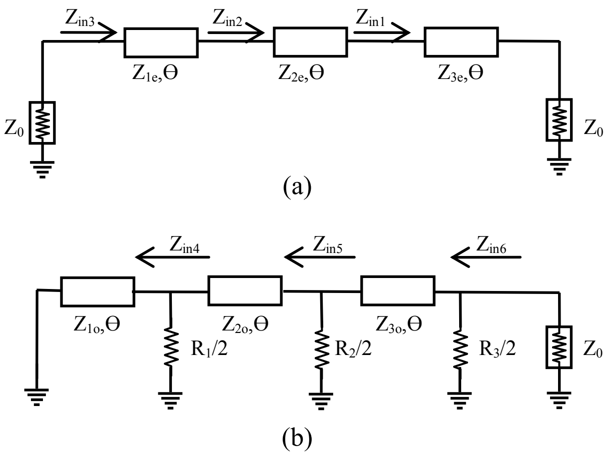

Fig. 2. (a) Even-mode (b) odd-mode analysis of the proposed miniaturized Wilkinson power divider.

The even-mode excited circuit, as it can be seen in Fig. 2 (a) must match $2Z_0$ to Z_0 at three designed frequencies. The relationship between three frequencies can be described as f_1, f_2= P_1f_1, and f_3 = P_2f_1, where P_1 and P_2 indicate the frequency ratio. Under this demonstrated condition, the relationship between input impedance and even-mode impedance at the specific transmission line length shown in Fig. 2 (a) can be express by these equations

$$Z_{in1}=Z_{3e}\,\frac{Z_0+jZ_{3e}\tan(\theta)}{Z_{3e}+jZ_0\tan(\theta)} \tag{1}$$

$$Z_{in2}=Z_{2e}\,\frac{Z_{in1}+jZ_{2e}\tan(\theta)}{Z_{2e}+jZ_{in1}\tan(\theta)} \tag{2}$$

$$2Z_0=Z_{in3}=Z_{1e}\,\frac{Z_{in2}+jZ_{1e}\tan(\theta)}{Z_{1e}+jZ_{in2}\tan(\theta)} \tag{3}$$

Since the parameters Z_0 and electrical length θ are known coefficient, so the values of Z_{1e}, Z_{2e}, and Z_{3e} are directly calculated solving non-linear equations. Which are derived from "(1)" to "(3)" for the designed frequency ratio of P_1 = 1 and P_2 = 1. The detailed of the derived equations for dual-band power divider at two arbitrary frequency ratios are given in [7]. The calculated even-mode impedances of proposed 3-section Wilkinson power divider are Z_{1e} = 94.66Z ,Ω_{2e} = 82.50Ω, and Z_{3e} = 71.35Ω.

Similarly, to satisfy the ideal matching and isolation performance at the output ports 2 and 3 for odd-mode excited circuit, the relationship between different parameters shown in Fig. 2 (b) can be express as

$$Z_{in4}=\frac{jR_1Z_{1o}\tan(\theta)}{R_1+j2Z_{1o}\tan(\theta)} \tag{4}$$

$$Z_{in5}=Z_{2o}\,\frac{Z_{in4}+j2Z_{2o}\tan(\theta)}{Z_{2o}+jZ_{in4}\tan(\theta)} \tag{5}$$

$$Z_{in6}=Z_{3o}\,\frac{R_2Z_{in5}+jZ_{3o}(R_2+2Z_{in5})\tan(\theta)}{Z_{3o}(R_2+2Z_{in5})+jR_2Z_{in5}\tan(\theta)} \tag{6}$$

The same approach is adopted to synthesize the odd-mode impedances values from non-linear equation derived from "(4)" to "(6)". The calculated odd-mode impedances values are Z_{1o} = 80.06Ω, Z_{2o} = 74.72Ω, and Z_{3o} = 56.17Ω. After the odd- and even-mode analysis, the width and length of three coupled lines are calculated by using Line-calculator tool available in Keysight Advanced Design System (ADS).

The output ports isolation of a power divider primarily depend upon the values of isolation resistors. The resistors values are optimized for best isolation values for the whole frequency band by using an EM simulator. The optimized values of three isolation resistors are R1 = 120Ω, R2 = 220,Ω330 = 3and R ,Ω .which can corresponded to commercially available values

Furthermore, the coupling features of three parallel coupled-lines are also investigated in the design process. The width of the coupled-lines and spacing between the coupled-lines are chosen through EM simulations accounting for practical considerations. The spacing between the coupled-lines should be wide enough so that it can easily accommodate commercially available SMD resistor. The coupling coefficients for three coupled-lines are C_a = -22.01 dB, C_b = -20.01 dB, and C_c = -18.5 dB. A taper is used to connect two coupled-lines have different line width in order to avoid a step change in impedance. After that, the optimization was performed for accommodating additional line length adds due to the taper. The final designed values of all the parameters for the proposed 3-section power divider are shown in Fig. 3.

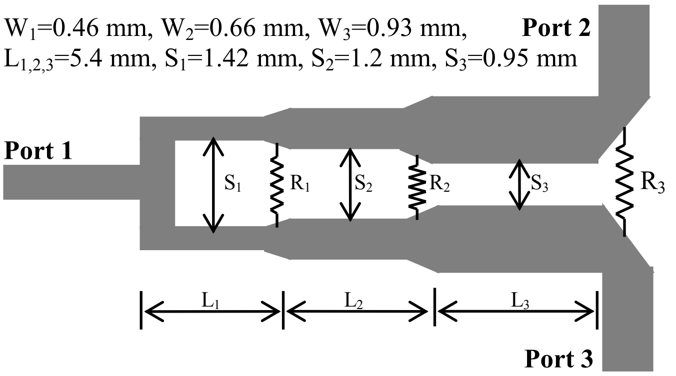

Fig. 3. Layout of the proposed miniaturized Wilkinson power divider.

III. Fabrication and Measurement

A FR4 Printed Circuit Board (PCB) with a relative permittivity of 4.7 and a 0.8 mm thick substrate is used to validate the design of the proposed power divider. The photograph of the realized splitter circuit is shown in Fig. 4 which equally splits the input power into two output ports 2 and 3. The overall physical dimensions of the realized power divider, except for three additional 50Ω transmission lines for measurement at the inputs and output ports, are about 18×3 mm^2. Since the design is based on coupled lines, the layout is more compact with a reduction in size of more than 60% compared to the conventional design at 3.5 GHz. Finally, the scattering parameters are measured using a Vector Network Analyzer [9].

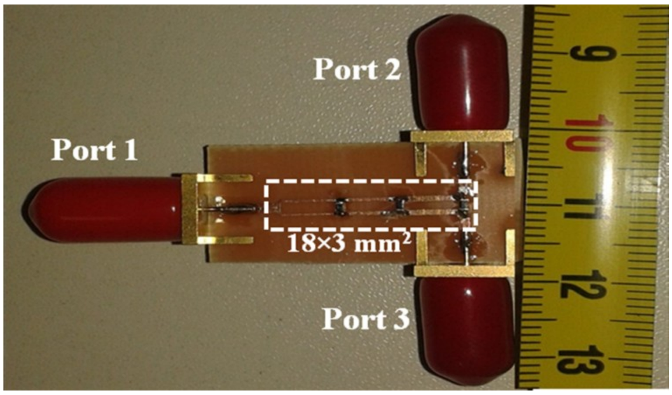

Fig. 4. Photograph of the proposed miniaturized Wilkinson power divider.

The measured insertion losses of the fabricated power divider along with the simulated performance are shown in Fig. 5. The measured values of insertion loss (S21 and S31) are in the range of -3.3 to -3.8 dB in the L- and S-band for the frequency range of 0.9-4.1 GHz. The measured S21 is -3.3 dB at the design frequency of 3.5 GHz, which is very close to simulated ones. The measured return (S11) loss is lower than -10 dB for the frequency range of 0.9-4.1 GHz as shown in Fig. 6.

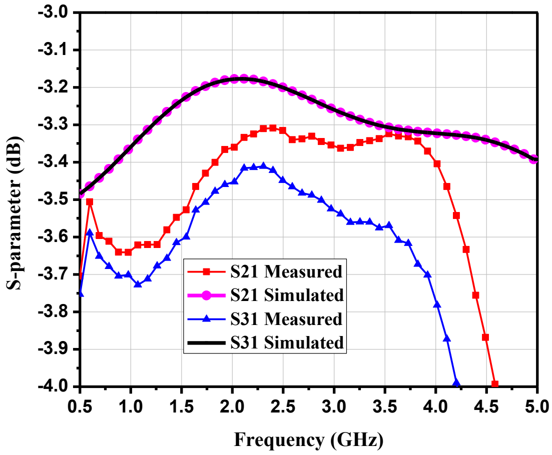

Fig. 5. S21 and S31 of the proposed miniaturized Wilkinson power divider.

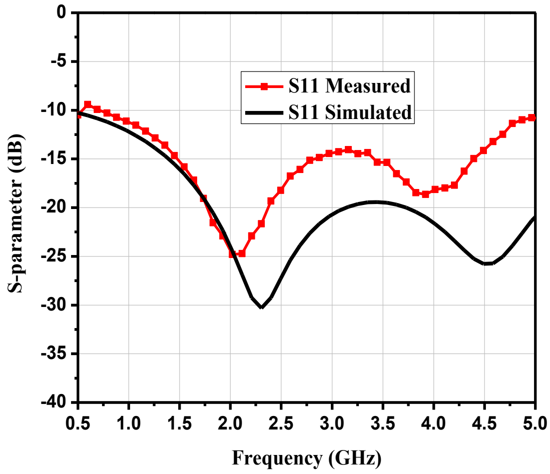

Fig. 6. S11 of the proposed miniaturized Wilkinson power divider.

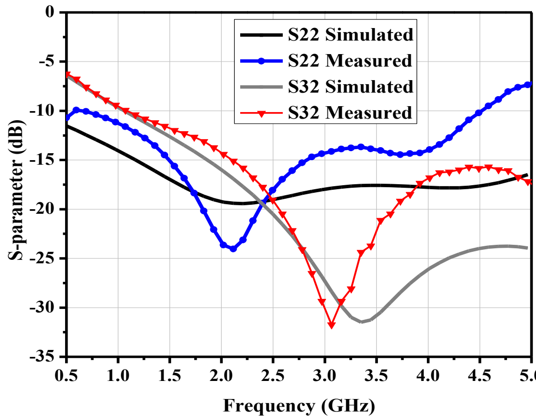

Fig. 7. S22 and S33 of the proposed miniaturized Wilkinson power divider.

The measured and simulated values of S22 and S32 are shown in Fig. 7, with isolation better than 20 dB at 3.5GHz and output ports reflection losses lower than -10 dB throughout the band. Fig. 8 shows the phase and magnitude difference between ports 2 and 3, the measured phase and magnitude difference are about ±0.05 dB and ±0.5 degrees, respectively. This indicates a good in-phase performance throughout the band. The small difference in measured and simulation results are caused by substrate dielectric material losses, and fabrication errors.

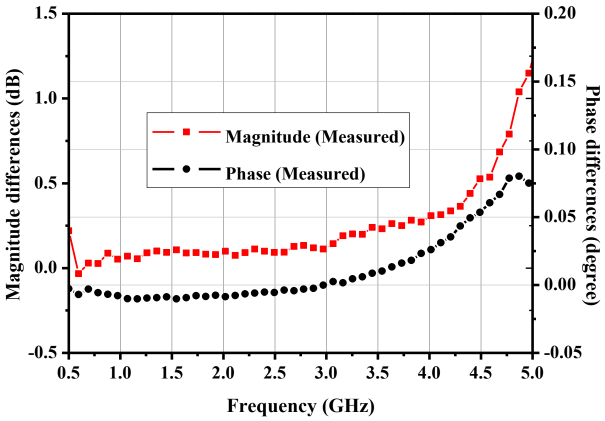

Fig. 8. Magnitude and phase deference between ports 2 and 3 of the proposed miniaturized Wilkinson power divider.

Table 1. PERFORMANCE COMPARISON OF START-OF-THE-ART WPDs AND PROPOSED WILKINSON POWER DIVIDER

Referen ces	**Proces s h(mm)**	**Topology**	**Inserti on losses (dB)**	**Operational Frequency (GHz) & Bandwidth (%)**	**Circuit Area (mm^2)**
2013 PIER [6]	1.57 FR4	Multi-stage, Asymmetric	1.6-2.5 6.8-8	0.7-2.15 GHz (100%)	83×8.8
2011 MTT [7]	0.76 Duroid	Multi-stage, Symmetric	3.1-3.8	0.7-2.6 GHz (115%)	54×4.2
2011 MTT [8] (Exmp. 2)	0.8 Duroid	Multi-stage, Asymmetric	2.2-3 4-4.8	0.8-2.1 GHz (90%)	83×8.5
2006 MTT [3]	1.27 NA	Multi-stage, Asymmetric	1.7-2.2 4.6-5.4	0.75-2.2 GHz (100%)	50×10
This work	0.8 FR4	Multi-stage, Symmetric	3.3-3.8	0.9-4.1 GHz (128%)	18×3

The operational bandwidth is defined as the frequency band where measured S11 < -10 dB. Based on this principle, the measured results from the realized power dividers is compared with other state-of-the-art published results, as shown in Table 1. The occupied area of the proposed miniaturized power dividers is more than 60% smaller than the other published multi-stage power dividers. The measured fractional bandwidth is also higher compared to recently published results, as shown in Table 1.

IV. Conclusion

In summary, microstrip based coupled lines are used to design a miniaturized Wilkinson power divider for ultra-wideband operation. The even- and odd mode impedances are calculated for small size and ultra-wideband operation. In order to validate the proposed design, two-way 3-section power divider is realized on FR4 substrate. Measured insertion and transmission losses are also compared to other start-of-the-art published measured results. The comparison includes the measured insertion loss, transmission losses, and the occupied area of the fabricated multi-stage power dividers in L- and S-band. The proposed power divider is applicable to microwave integrated circuits (MICs) requiring small size and wide operational bandwidth.

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