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Compact N-Way Recombining Wilkinson Power Dividers for SatCom Applications

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***Abstract* — A number of low-insertion-loss Wilkinson power dividers for the Ka-band are presented. Uneven division ratios are achieved by modifying the traditional Wilkinson divider design with recombination stages. Reducing insertion loss is a key goal to ensure the design of power efficient local oscillator (LO) distribution networks. For the design, a resistor model is investigated in a full-wave EM simulation environment. The average insertion loss from 27 to 31.5 GHz for various dividers ranges from 0.4 dB to 1.1 dB compared to the ideal insertion loss. The designed dividers offer promising performance for the implementation of modern communication and radar systems with complex distribution networks.**

***Keywords* — Wilkinson, three-way, recombining**

I. Introduction

Power dividers are essential components for signal distribution in modern radar and communication systems. In phased arrays, each path needs a distinct LO-signal to ensure accurate beamforming and signal processing. The traditional Wilkinson power divider is highly effective in creating 2^n power divisions to distribute the LO-signal. Furthermore, Wilkinson dividers offer low insertion loss and high port isolation. However, at high frequencies, design challenges arise due to parasitics of Surface Mounted Device (SMD) components and transmission lines. Additionally, achieving non-2^n splits, such as three- or five-way divisions, is particularly difficult in planar structures due to overlapping paths. These uneven division requirements are critical in many advanced applications where efficient signal power management and distribution is necessary in order to reduce LO-signal loss to a minimum by the dividers.[1]

Traditional non-2^n dividers, as shown in [1], require non-planar structures for implementation. Dividers with coupled lines, as demonstrated in [2] and [3], are planar but suffer from low isolation and strict limitations with respect to line spacing. Other dividers, also based on Wilkinson dividers as discussed in [4], [5], [6], and [7], require numerous resistors or capacitors within a small area. By the use of these resistive components, parasitic effects become apparent, making them primarily suitable for lower frequencies, which in turn leads to challenges for higher frequency applications. In addition, recombining Wilkinson dividers with a small number of resistors have been designed for low frequencies, as shown in [8]. In this paper, the design and implementation of various recombining dividers with even and uneven ratios up to a division factor of 12 within a compact structure are discussed for the frequency range of 27 GHz to 31.5 GHz. These dividers are optimized for low loss performance, ensuring efficient signal distribution in advanced radar and communication systems.

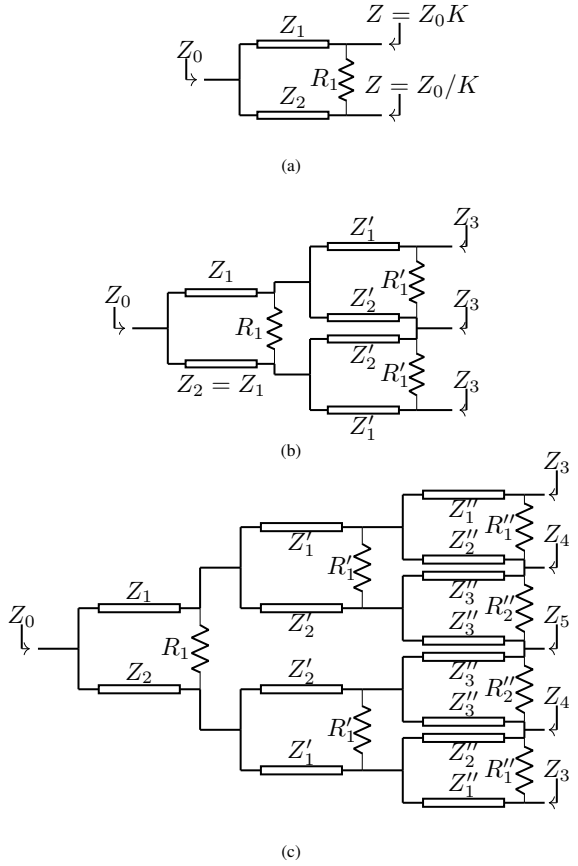


Fig. 1. Different types of Wilkinson dividers: (a) two-way divider with equal or unequal power division; (b) three-way divider with two stages and recombining paths; (c) five-way divider with three stages and recombining paths

II. Design and Implementation

The Wilkinson dividers designed in this work are fundamentally composed of combinations of two-, three-, and five-way dividers. The two-way divider is based on a standard symmetric Wilkinson design as seen in Fig. 1a. The calculation of the line impedances Z_1 and Z_2 and the resistor R_1 of the

Wilkinson divider are [1]:

$$Z_2 = Z_0\sqrt{\frac{1+K^2}{K^3}} \tag{1}$$

$$Z_1 = K^2 Z_2 = Z_0\sqrt{K(1+K^2)} \tag{2}$$

$$R_1 = Z_0(K + \frac{1}{K}). \tag{3}$$

The power ratio is defined as $K^2 = \frac{P_2}{P_1}$, where Z_0 represents the source impedance. All line lengths are $\lambda/4$. An unequal power division introduces a mismatch at the output, which can be mitigated by a quarter-wavelength transformer at the cost of bandwidth and size.

The three-way divider, as shown in Fig. 1b, features a two-stage recombining structure composed of both an equal and an unequal Wilkinson divider. The first stage of the three-way divider consists of an equal Wilkinson divider. In the second stage, dividers with a power ratio of 2:1 are used. Combining the middle paths with 1/6 of the power each, results in an overall power ratio of 1/3 for all three output paths. With the power ratio K^2 and Z_0 all other parameters of the single stages can be determined.

The five-way power divider shown in Fig. 1c includes an initial equal division in its first stage, followed by two unequal divisions with a power ratio of 2:3 in the second stage. The third stage utilizes a combination of two equal dividers in the center and two outer unequal dividers with a power ratio of 2:1. After combining, respectively, two central paths, a uniform 1/5 power split is achieved across all five output paths. The varying output impedances are matched to $50\,\Omega$ by quarter-wavelength transformers.

A. Modeling and Verification of the Resistors

To ensure the dividers operate appropriately up to $31.5\,\mathrm{GHz}$, a simulation model was implemented in a full-wave EM simulation environment. This model includes high-frequency resistors from the Vishay CH series, as depicted in Fig. 2. The resistor consists of an alumina body (beige), an ohmic sheet at the bottom (green), and copper pads (yellow). The resistance can be adjusted via the resistance per square meter of the ohmic sheet based on the area of the resistor. Resistance values of $50\,\Omega$, $100\,\Omega$ and $150\,\Omega$ are available in SMD-sizes 0402 and 0201. To analyze the impact of resistor size, PCBs with a simple transmission line, terminated with $50\,\Omega$ resistors in sizes 0402 and 0201, were

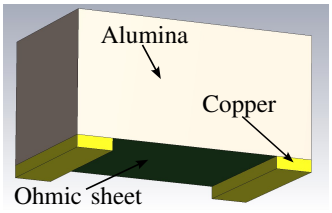


Fig. 2. Resistor modelled in a full-wave EM simulator with ohmic sheet, alumina as body and copper pads

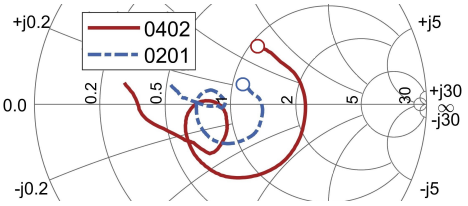


Fig. 3. S_{11} of the resistors from 20 GHz (marked) to 40 GHz

built. This setup allowed for the measurement of the impedance matching of those resistors. Figure 3 shows a comparison of the measurements in a Smith chart. The 0201 resistor demonstrates significantly better performance, due to fewer parasitic effects, making it a more suitable choice for line termination.

B. Design of the Wilkinson Dividers

The calculated line impedances are adjusted based on the available resistor values. Versions of the two- and three-way dividers, using both 0201 and 0402 resistors for comparison, are fabricated on Panasonic's Megtron8(N) with a substrate height of $178\,\mu\mathrm{m}$. Additionally, a three-stage five-way divider is built exclusively with 0402 resistors, as a design with 0201 resistors would add too much complexity due to the tighter spacing. The final parameters, optimized for low insertion loss of the two-, three-, and five-way dividers, are listed in Table 1.

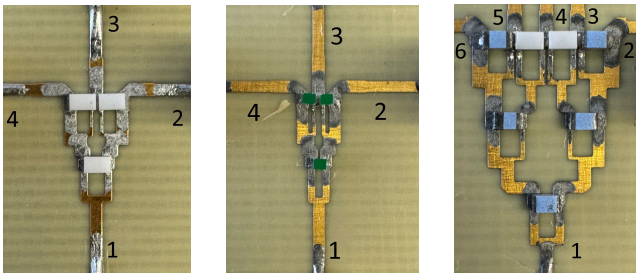
Table 1. Values for the two-, three- and five-way divider

Stage	**Parameter**	**Values in Ω**		
		Two-Way	Three-Way	Five-Way
1st Stage	Z_1	70.7	70.7	70.7
	Z_2	70.7	70.7	70.7
	R_1	100	100	100
2nd Stage	Z_1'	-	50	58.3
	Z_2'	-	100	87.5
	R_1'	-	100	100
3rd Stage	Z_1''	-	-	40.8
	Z_2''	-	-	82
	Z_3''	-	-	87
	R_1''	-	-	100
	R_2''	-	-	150

Figure 4 shows the three-way dividers manufactured with 0402 and 0201 resistors and the five-way divider with 0402 resistors on a PCB. The ports of the dividers are connected to Mini-SMP connectors. The two-way and three-way dividers are also combined to build PCBs with division factors of 6 and 12, while three cascaded stages of two-way dividers are used to achieve a division factor of 8.

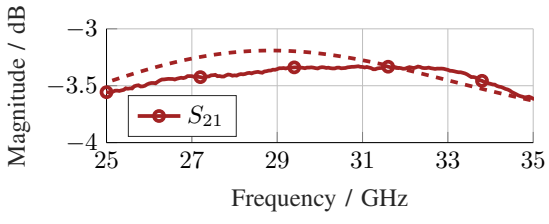
III. Measurement Results

Figure 5a illustrates the transmission coefficient of the two-way power divider with a 0402 resistor. The insertion loss averages around $3.4\,\mathrm{dB}$ in the frequency range of $27\,\mathrm{GHz}$ to $31.5\,\mathrm{GHz}$. Furthermore, Fig. 5b shows the input and output reflection coefficients, which remains below $-10\,\mathrm{dB}$ from $26.5\,\mathrm{GHz}$ to $33.5\,\mathrm{GHz}$ and demonstrates a similar behavior compared to the simulation.

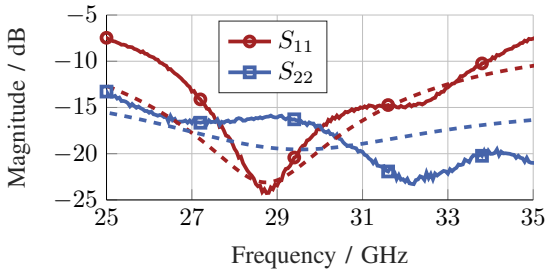


(a) (b) (c)

Fig. 4. The fabricated three- and five-way dividers on PCBs: (a) three-way with 0402 resistors; (b) three-way with 0201 resistors; (c) five-way with 0402 resistors



(a)



(b)

Fig. 5. Simulated (dashed) and measured (solid) S-parameters for the two-way divider with 0402 resistor: (a) transmission; (b) reflection

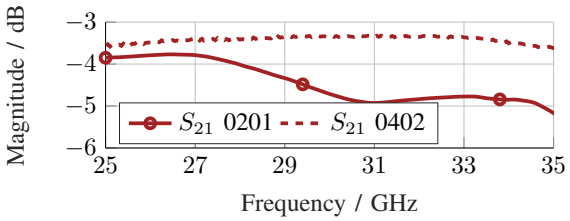
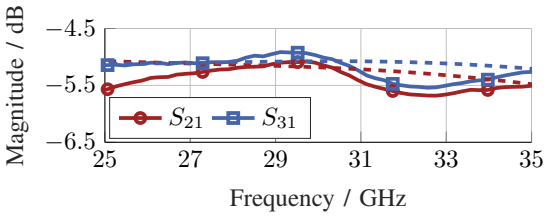
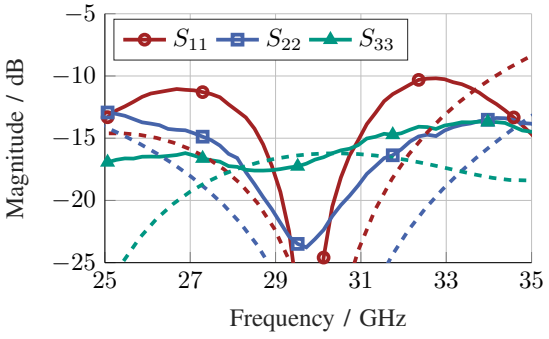


Fig. 6. Measured transmission coefficients for the two-way dividers with 0402 and 0201 resistor



(a)



(b)

Fig. 7. Simulated (dashed) and measured (solid) S-parameters for the three-way divider with 0402 resistors: (a) transmission; (b) reflection

Figure 6 compares the transmission coefficient of the two-way divider with 0402 resistors to that of the two-way divider with 0201 resistors. Although the 0201 resistor shows fewer parasitic effects, its transmission coefficient is lower than that of the 0402 resistor, with an average loss of 4.4 dB across 27 GHz to 31.5 GHz. Although the parasitic effects of the resistor are lower, the design requirements become significantly more demanding because of the smaller footprint of the resistor. The coupling due to the closer spacing of the transmission lines in the 0201 design introduces larger parasitic effects than those caused by the larger resistor.

The transmission coefficient of the three-way divider with 0402 resistors, shown in Fig. 7a, align well with the simulated results, with a ripple of only 0.5 dB. The splitter achieves a low average transmission loss of 5.2 dB between 27 GHz and 31.5 GHz, which is close to the ideal attenuation of 4.8 dB. The difference between the insertion loss at port 2 and port 3 is less than 0.1 dB. Port 2 and 4 are supposed to show identical results due to the symmetric design. Figure 7b illustrates an input and output reflection coefficients below −10 dB across the entire frequency range. However, the measured input and output return losses are slightly higher than the simulated values, likely due to the solder effects on the transmission lines near the resistors. Figure 8 presents the comparison of the measurement results for the three-way divider using 0402 and 0201 resistors. As with the two-way divider, the 0402 resistor performs better despite its larger parasitic effects. The coupling of transmission lines in the 0201 design causes a 0.5 dB higher average insertion loss of 5.7 dB.

The simulated and measured transmission coefficients of the five-way divider are presented in Fig. 9a, the reflection coefficients are shown in Fig. 9b. The transmission coefficients show a low average insertion loss of 7.9 dB across all five outputs, while the ideal insertion loss is 7 dB. The increased insertion loss, compared to the two- and three-way dividers, is due to the use of additional stages. Also in the third stage of the five-way divider, the six central transmission lines are closely spaced, leading to significant parasitic coupling, even with the 0402 resistor configuration. Overall, the measured

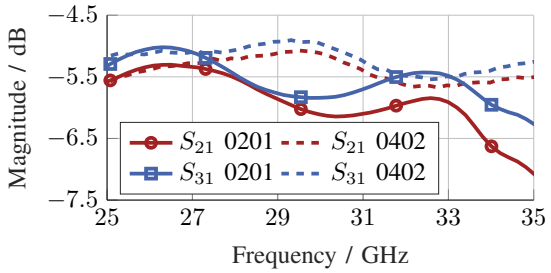
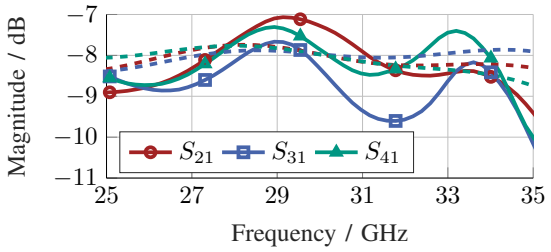
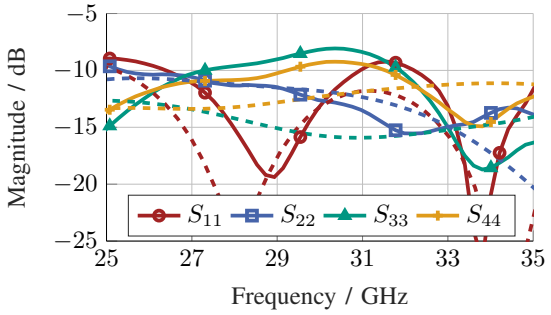


Fig. 8. Measured transmission coefficients for the three-way dividers with 0402 and 0201 resistors

transmission aligns well with the simulated one, although a larger ripple of 2 dB is observed, which can likely be attributed to larger amounts of solder. The measured S_{11} matches well with the simulated S_{11}. The measured S_{22} remains below $-10\,\mathrm{dB}$ across the entire frequency range, while S_{33} and S_{44} are measured below $-8\,\mathrm{dB}$ and $-9\,\mathrm{dB}$. Ports 5 and 6 show similar results to Ports 3 and 2 due to the symmetric design.



(a)



(b)

Fig. 9. Simulated (dashed) and measured (solid) S-parameters for the five-way divider with 0402 resistors: (a) transmission; (b) reflection

Finally, Fig. 10 presents the transmission coefficients of all fabricated dividers with 0402 resistors. The largest ripple is observed in the five-way divider due to the large concentration of SMD components and solder and the closely spaced transmission lines. Table 2 compares the measured average insertion loss to the ideal loss, showing only a minimal difference (Delta) from $0.4\,\mathrm{dB}$ to $1.1\,\mathrm{dB}$ for the different power dividers.

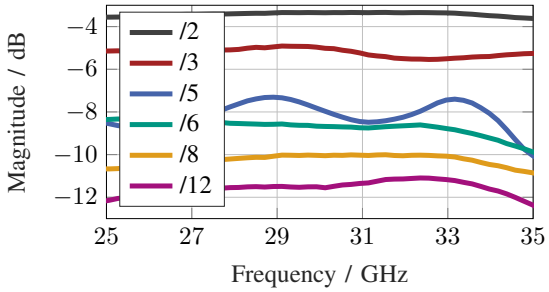


Fig. 10. Measured transmission coefficients of all fabricated dividers with 0402 resistors

Table 2. Comparison of ideal and measured average insertion loss from 27 GHz to 31.5 GHz for various dividers with 0402 resistors

Divider	Ideal Loss / dB	Measured Loss / dB	Delta / dB
/2	3.0	3.4	0.4
/3	4.8	5.2	0.4
/5	7.0	7.9	0.9
/6	7.8	8.6	0.8
/8	9.0	10.1	1.1
/12	10.8	11.8	1

IV. Conclusion

In this work, power dividers with division ratios of up to 1:12 were designed and characterized. By the usage of a simple resistor model, the dividers were successfully designed with low insertion loss over a frequency range of 27 GHz to 31.5 GHz. A comparison between 0402 and 0201 resistors demonstrates that the reduced parasitic effects of the 0201 resistor are dominated by additional couplings introduced by the modified circuit layout with smaller gaps between the transmission lines.

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