4-Way Microstrip Wilkinson Power Splitter at Frequencies of Millimeter Waves

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Abstract— **In this paper, we reflect on the new challenges in the Wilkinson power splitter design for present and future applications at frequencies of millimeter waves. The advantages and disadvantages of various surface mounting configurations are discussed, focusing on easy installation and repeatable RF performance. The paper also outlines our efforts toward the miniaturization, compactness, and geometrical efficiency of the Wilkinson power splitters. Combining Wilkinson 2-way splitters of various power ratios into more complex power distribution networks is a tedious task that requires layout customization and careful tuning of basic RF building blocks. These design considerations are described in the example of a 4-way Wilkinson splitter on Alumina substrate for operational frequency band 25 – 35 GHz. The design prototypes have been successfully produced and tested with the results presented here.**

Keywords—**Wilkinson power splitter, ceramic substrate, even mode, resistors, hybrid beamforming, millimeter waves.**

I. Introduction

For many years, Wilkinson power splitters have been playing a prominent role in RF systems as RF designers' first choice for RF power distribution. These low-loss passive radio frequency (RF) components conveniently split and distribute input signal into multiple signals in various proportions to different elements in a larger RF system. RF power amplifiers and antenna arrays are two main applications where RF power distribution is traditionally required. In the amplifier application, a power splitter splits the signal to feed multiple low-power amplifiers and then recombines the signals from the amplifiers into a high-power output signal. In antenna array applications, power splitters are routinely used within a phased antenna array system to feed multiple antenna elements at different amplitude and phase levels.

Current developments in fifth-generation (5G) technology, the Internet of Things (IoT), and Industry 4.0 require an efficient, reliable, and affordable technology that meets the performance demand in a frequency band of interest. For some of these applications, hybrid beamforming is often implemented as it offers a practical trade-off between analog and digital options. Hybrid beamforming reduces the complexity of digital beamforming, improves thermal management, and maintains a reasonable level of performance provided by the limited digital processing. Two-stage hybrid beamforming employs digitally controlled RF chains, Wilkinson power splitters, and analog phase shifters [1]. As a fundamental building block, the Wilkinson power splitter must evolve to respond to the new challenges in these modern communication systems. Wilkinson power splitters must be compact, easy to integrate, and must exhibit good RF performance at operational frequencies stretching into millimeter waves.

Many variations of Wilkinson splitters have been reported that target a specific goal, such as broadened bandwidth, suppressed harmonics, low insertion loss, compactness, or low manufacturing cost. Ekinge [2] presented a method of synthesizing matched broadband power splitters with multiple coupled quarter-wave transforming sections and resistors. Deutschmann and Jacob [3] introduced a new type of ultra-broadband compact power splitters for the frequency range of 2 to 40 GHz. Demir et al. [4] proposed a model of an efficient wideband power splitter for planar antenna arrays with Klopfenstein impedance taper to reduce the physical dimensions. An extensive overview of different configurations and variations of Wilkinson power splitters can be found in [5].

II. Design Considerations

A. Basic Theory

A power divider (splitter) is an RF device that divides input RF signal into multiple segments that appear at its output ports. A power splitter may also be used to combine the signals if the flow of the RF power is in the opposite direction. Ideally, a power splitter is a perfectly matched, reciprocal, and lossless RF device [6]. A perfect match means no reflections from any of its ports, i.e., the scattering parameters $S_{11} = S_{22} = S_{33} = 0$. A reciprocal RF device is one in which the transmission of a signal between any two ports does not depend on the direction of propagation, i.e., the scattering parameters $S_{jk}=S_{kj}$, for $j,k=1,2,3$. Finally, a lossless device means no losses inside the structure, $\sum_{j=1}^{3}\left|S_{jk}\right|^2 = 1$ for $j,k=1,2,3$. An ideal (matched, reciprocal, and lossless) power splitter is not physically realizable. Wilkinson power splitter satisfies two of the three properties defined above. It is a preferred option compared to other types of splitters (resistive and T-junction) that are characterized by poor isolation between the output ports.

The Wilkinson power splitter, shown in Fig. 1, is an RF device capable of splitting the RF power in different ratios with all matched ports and excellent isolation between the output ports. It is named after Ernest Wilkinson [7], who invented it in the 1960s. The design of the Wilkinson splitter is composed of one or more quarter-wave transforming sections used to transform the impedance at the input port to the impedance at the output port. One can achieve a good match at all ports in a desired frequency band based on the number of quarter-wave sections. Resistors at the junctions between the quarter-wave transformers enable good output return loss and isolation between the output ports. When the outputs are connected to matched loads for an equal-split Wilkinson, the voltages along each output transmission line are of the same magnitude and phase, with no power dissipated in the resistors [2].

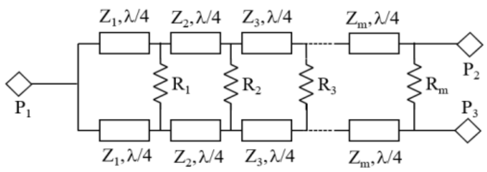

Fig. 1. Basic structure of Wilkinson power splitter with equal power split ratio.

B. *Even and Odd Mode Analysis at High Frequencies*

Wilkinson power splitters are designed using the even and odd mode method. Two identical signals are applied to the output ports in the even mode, and the input is terminated to 50 Ω. Such an excitation produces zero magnetic fields through the plane of symmetry of the splitter. The analysis can further be performed on half of the structure and practically turns into a problem of matching 50 Ω to 100 Ω using a single or multiple quarter-wave transforming sections. These quarter-wave transforming sections in one branch often couple to their counterparts in the other branch and must be treated as couplers with different impedances in even and odd modes. The number of quarter-wave sections determines the range of operational frequencies over which the power splitter exhibits an acceptable input return loss. For example, a single quarter-wave transformer of impedance 70.7 Ω used to transform 100 Ω to 50 Ω results in the input return loss of 20 dB over 40% bandwidth. A series of five quarter-wave transformers of the Chebyshev type produces an equal-ripple input return loss of 20 dB over 9:1 bandwidth.

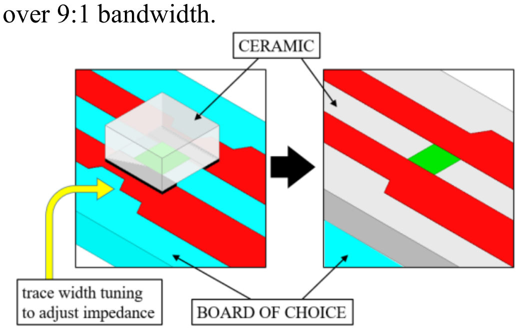

Fig. 2. The impact of resistors on the power splitter performance in even mode and the proposed solution to minimize this effect.

If assumed ideal and with zero electrical length, resistors play no role in this impedance matching problem. However, at high frequencies of millimeter waves, physical resistive sheets connected to the transmission line will affect its impedance and may have a significant electrical length of λ/8 or more. This especially applies if the resistors are installed on the power splitter structure as single surface mount ceramic chips. To account for the electrical impact of the resistors in even mode, RF designers must adjust the electrical lengths of the quarter-wave transforming sections and their line widths in the areas where resistors are installed (Fig. 2). This requires an effort and may be avoided if both the power splitter structure and resistors are designed on a single ceramic platform, as proposed in this paper.

In odd-mode analysis, two signals of identical amplitude and opposite phase are applied to the splitter outputs. This excitation creates an electric wall at the plane of symmetry. Half the structure is then analyzed with half of each resistor connected to the ground (Fig. 3) and the shorted T-junction at the input. Since this T-junction is directly connected to the first quarter-wave section, the short will ideally transform into open at the location of the first resistor. Hence, the odd-mode analysis becomes an impedance-matching problem with multiple resistors and quarter-wave transforming sections between the resistors. Similar design considerations explained previously for even mode also apply to odd mode. Values of impedances and resistance values for different configurations are elaborated in detail in [2].

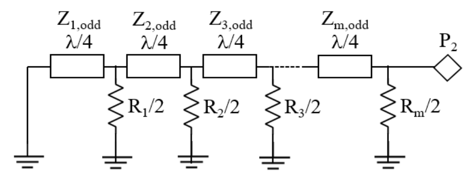

Fig. 3. Power splitter structure in odd mode.

RF designers may tune to desired resistor values by adjusting the coupling between the quarter-wave transforming sections. This can be achieved through different gaps between the sections. It should be noted that different gap also affects even mode impedances. Therefore, the design process requires a few iterations until desired values of trace line widths, gaps, and resistance values are achieved. RF designers will often opt to significantly increase the value of the last resistor (R_m) and completely avoid it in the splitter structure without a significant impact on the splitter performance. This simplifies the practical realization as this resistor's high value poses a challenge during thin or thick film resistor manufacturing.

If a power splitter is realized in an inhomogeneous medium such as a microstrip, its effective permittivity may differ in two modes. The quarter-wave transformers may have very different electrical lengths in two modes due to different phase velocities. This creates a design obstacle that is very difficult to overcome and results in poor functionality of the corresponding splitter.

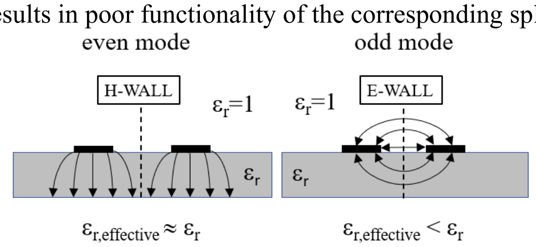

Fig. 4. Different distribution of electric field resulting in a different relative permittivity of even and odd mode.

Many authors have previously treated the problem of different lengths for even and odd modes. March [8] used lumped elements to achieve phase-velocity compensation in the two modes, while Podell [9] proposed the use of teethlike or sawcut shapes in the "wiggly" coupler for the same purpose. The use of anisotropic substrates [10] or dielectric overlays [11] has also been suggested as a solution to the problem described above. All of these solutions are related to specific applications and are too bulky for a compact solution sought in modern communication systems.

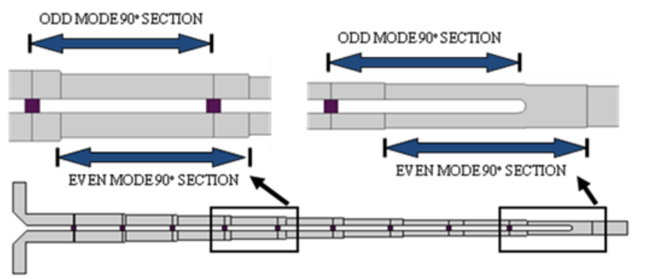

Fig. 5. Different physical lengths and positions of quarter-wave transforming sections in even and odd modes to compensate for different phase velocities in even and odd modes.

To solve the issue of different electrical lengths in even mode and odd mode, the quarter-wave transforming sections do not necessarily have to be separated by the shunt resistive elements, as is the case in the conventional Wilkinson power splitter [6]. In even mode (Fig. 5), this technique would still result in a traditional multi-section quarter-wave transforming network optimized using Chebyshev polynomials [5]. In odd mode, however, each transmission line section between the two consecutive shunt resistors will consist of two elements with different characteristic impedances. Still, their electrical lengths would add up to a total of 90°.

C. *Different Mounting Options*

Power splitters with unique advantages and disadvantages may be realized on different planar platforms—microstrip, stripline, and coplanar waveguide. A microstrip platform provides the most straightforward design and affordable manufacturing process, as no bonding of multiple RF layers is required. However, the RF structure on a microstrip chip is isolated from the surrounding RF environment from one side only—the grounded one—and thus may be prone to undesired RF effects. A power splitter on a microstrip chip may be designed in a few distinct configurations, such as "flip chip," "flip chip with the ground wrap," and "true surface mount" (Fig. 6). In a flip chip configuration, the RF structure is in direct contact with the application (test) board that provides for a good impedance match. However, the microstrip chip does not have a ground plane on the side opposite the RF signal structure. It, therefore, is not isolated from the impact of the surrounding RF environment. This issue is resolved with the flip chip configuration with the ground wrap that completely encloses the RF structure. A significant disadvantage of both the flip chip and the flip chip with the ground wrap configurations is their reliance on the electrical properties of the application board. Since the RF structure is sandwiched between the microstrip chip and the application board, a significant amount of the electromagnetic field runs through the application board to the grounded plane on the opposite side. Power splitters realized in these two configurations are designed for a specific dielectric constant and thickness of the application board. If the customer installs the same power splitter on a different application board, the splitter won't probably be impedance matched.

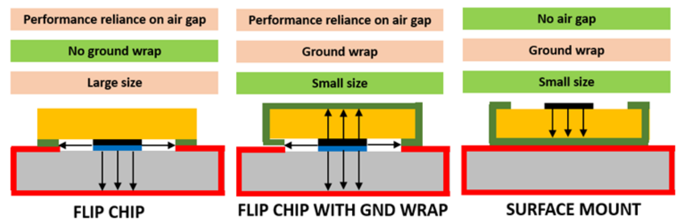

Fig. 6. Advantages and disadvantages of different mounting options.

In a surface mount configuration, the RF structure is placed on the top of the microstrip chip with the ground plane on the bottom. The chip is situated on the application board with the bottom ground plane connected to the board. The RF structure is electrically separated from the application board. Therefore, the electrical properties of the application board do not affect the performance of the power splitter except in the localized areas of the contact pads through which the power splitter is connected to the RF circuitry on the application board. Finally, the surface-mount configuration may also result in the most compact design of the power splitter if a substrate with a high dielectric constant is used.

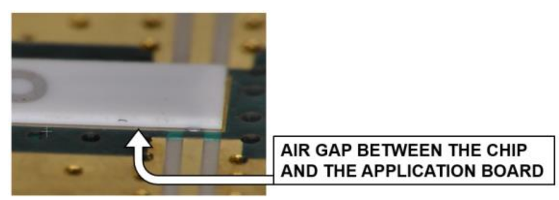

Fig. 7. Air gap between the microstrip chip (white) and application board (gold/green) that causes an inductive mismatch.

A few power splitters have been designed, manufactured, and tested to compare the performance in different configurations. Board thickness, substrate (chip) thickness, and total thickness were measured using a 5-digit micrometer. The conductor thickness was measured using a drop gauge on an unused blank board. It has been observed that the air gap thickness (Fig. 7) varies from 0 to 3 mil (0.076mm). This variation significantly affects the line impedances of the power splitter. The air-filled gap between the chip and the application board caused by thicker-than-expected metal thickness adds an undesirable inductive effect that affects VSWR and isolation. As a result of this analysis, the surface mount option was selected as the most attractive one, both commercially and technologically, as it avoids reliance on specific application board properties and the variability of the air gap between the chip and the board.

III. 4-WAY POWER SPLITTER MODELING AND TEST

A 4-way equal split power splitter at Ka-band frequencies has been designed on a 10-mil thick Alumina substrate to validate the proposed design techniques elaborated in the previous sections. The procedure consisted of designing a corresponding 2-way splitter first and then using this basic building block to realize a corresponding 4-way splitter. Combining three 2-way splitters into a compact 4-way structure requires a significant effort and expertise in layout customization. For example, the shape of the power splitters may be appropriately adjusted by bending the quarter-wave sections.

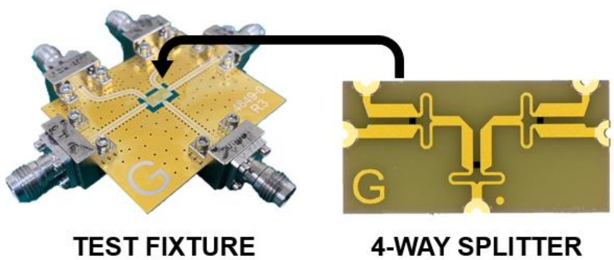

Fig. 8. 4-way power splitter: test fixture (left), chip (right).

The size of the power splitter (Fig. 8) has been reduced in the axial direction by bending the first quarter-wave transforming section into a U-shaped structure. The size of the 4-way splitter has been minimized to 6.35[mm]×3.18[mm]. The proposed 4-way splitter has been manufactured and tested to verify the design methodologies described in this paper. The splitter is characterized by 18 dB return loss, 20 dB isolation, and 2–2.5 dB insertion loss over the entire frequency band of interest (Fig. 9).

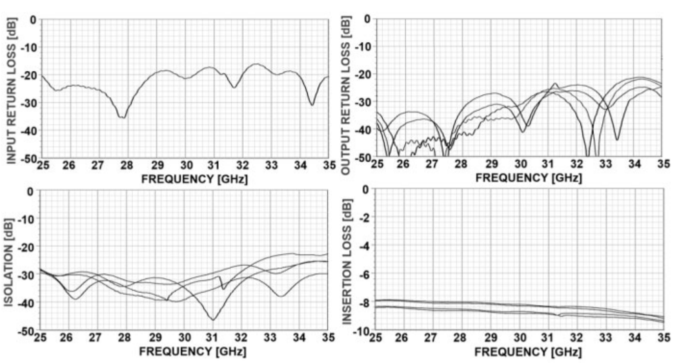

Fig. 9. 4-way power splitter RF performance, 25 – 35 GHz.

The design of Wilkinson 2-way splitters with the equal split ratio is based on: (1) even-mode and odd-mode analysis and (2) heavy reliance on the RF structure symmetries. For example, an electric wall (E=0 plane, virtual ground) in odd mode and a magnetic wall (H=0 plane) in even mode cut the splitter in identical halves. Hence, the entire simulation may be performed on half of the splitter, significantly reducing the simulated model's complexity and the required simulation time. On the other side, designing a Wilkinson power splitter with an unequal power ratio poses a significant challenge, as such symmetries do not exist.

Nevertheless, Wilkinson power splitters with unequal power ratios play a critical role in many phased-array applications, and more power splitters with more complex power ratios such as 3-way, 6-way, and others.

IV. CONCLUSION

Wilkinson power splitters will continue to play a significant role in RF power distribution systems. A large variety of power splitter topologies addressing a specific requirement for a broadband, low insertion loss, or good match is proof of their popularity and extensive use in beamforming networks, RF amplifiers, and other RF applications. This paper presented design methodologies relevant to developing surface-mount Wilkinson power splitters at millimeter wave frequencies. These advanced techniques could be easily implemented for arbitrary Wilkinson splitter configurations with any power split ratios and any number of outputs. The power splitter configurations proposed in this paper could also be deployed in various RF beamforming systems. The advantages and disadvantages of different mounting platforms have been discussed, with the conclusion that the surface-mount option provides superior performance compared to the alternatives. Finally, we developed a Wilkinson 4-way splitter to verify the proposed methodology at frequencies 25 – 35 GHz. The prototypes have been manufactured and successfully tested, providing evidence of the validity of the proposed advanced design techniques.

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