Resistive and Wilkinson Power Splitters at Frequencies of Millimeter Waves for Space Applications

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Mo Hasanovic(1) and Juan G. Ayala(1)

(1) Smiths Interconnect Americas
3477 SE Willoughby Blvd, Suite 103
Stuart, Florida, 34994, United States
Email: moamer.hasanovic@smithsinterconnect.com

INTRODUCTION

Power splitters are passive radio frequency (RF) components that are used to split and distribute an input signal into two or more signals in various proportions to different components in a larger RF system. These components have played a prominent role in RF systems for many years. Two of the main applications for power splitters are (1) distribution of input power to amplifiers and (2) distribution of a RF signal to antenna arrays. In the amplifier application, a power divider splits the signal to feed multiple low-power amplifiers and then to recombine the signals from the amplifiers into a high-power output signal. In antenna array applications, power dividers are used within a phased antenna array system to feed multiple antenna elements at different amplitude and phase levels. This RF structure enables electronic beam scanning as well as focusing the antenna beam on different directions as a function of the phase difference at individual antenna elements. There are many different types of power splitters reported and used in various RF applications. Resistive and Wilkinson types are among the most frequently used and integral components in many RF/microwave chains. The structure of these traditional passive components has been continuously changing to respond to new challenges in modern communication systems.

Current developments in fifth generation (5G) technology, Internet of Things (IoT), and Industry 4.0 require an efficient, affordable, and economically viable beamforming technology. For some of these applications, hybrid beamforming offers a practical trade-off between analog and digital options. It reduces the complexity of digital beamforming and improves the thermal management while maintaining a reasonable level of performance provided by the limited digital processing. Two-stage beamforming employs digitally controlled RF chains, power splitters and analog phase shifters [1].

In this paper, we compare a few power splitter technologies that could be employed in hybrid beamforming and present some of the advantages and challenges of various mounting options and platforms. This paper also describes our efforts directed toward the miniaturization, compactness, and efficiency of the proposed high frequency splitters. The splitters presented in this paper are of Wilkinson and resistive types and include both equal-split and unequal-split options that could be used as basic building blocks for more complex power-splitting needs. Many modern radar and satellite systems require a low insertion loss performance of their integral parts to accommodate stringent loss budgets and long communication paths. To meet this design requirement, the beamformer is often realized using suspended airline technology that provides a low effective dielectric constant and consequently low insertion loss. Design of a power splitter in suspended airline technology brings its own unique challenges that includes different effective dielectric constants of the even mode and the odd mode. In this paper, we describe an elegant algorithm to overcome the issue of different phase velocities of the even and odd modes in a Wilkinson splitter design realized in a suspended stripline.

BASIC THEORY OF RESISTIVE AND WILKINSON POWER DIVIDERS

A power divider (splitter) is an RF device that conveniently divides input power into multiple segments that appear at its output ports. A power divider may also be used to combine the power if the flow of the power is in the opposite direction. In its ideal form, a power divider is a perfectly-matched, reciprocal, and lossless RF device. A perfectly-matched power divider 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 $S_{21}=S_{12}$, $S_{13}=S_{31}$, etc. Finally, a lossless device means no losses inside the structure, i.e., $|S_{11}|^2+|S_{21}|^2+|S_{31}|^2= 1$, $|S_{12}|^2+|S_{22}|^2+|S_{32}|^2= 1$, and $|S_{13}|^2+|S_{23}|^2+|S_{33}|^2= 1$. An ideal (matched, reciprocal, and lossless) power divider is not physically realizable, but there are power dividers that satisfy two of the three properties defined above. Traditionally, three types of power dividers are widely used in RF systems—resistive type, T-junctions, and Wilkinson Power Dividers [2]. The resistive type and T-junction type are the least preferred power dividers owing to their poor isolation which is observed between the output ports in comparison with a Wilkinson power divider.

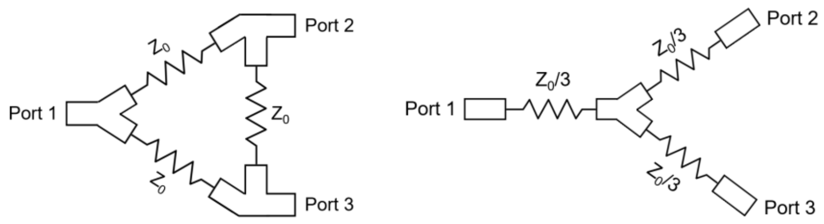

Fig.1. Two configurations of a resistive power splitter—delta (left) and wye (right).

Resistive power dividers are usually implemented with the same impedance at all ports. Two of the main configurations for a resistive power divider, the "delta" and the "wye," are shown in Fig 1. Resistors used in these simple RF devices provide a good impedance match at each of the three ports. However, the resistive structure introduces a significant loss that is one of the major disadvantages for this type of power splitter. If the power at the ports is calculated, it may be shown that $P_{OUT2} + P_{OUT3} = 0.5P_{IN}$, i.e., half of the input power is lost inside the power divider structure. Isolation between the output ports is not necessarily achieved with the resistive power divider [3]. The input impedance looking into each port of the resistive power splitter can be calculated using the following formula:

$$Z_{in} = R + \frac{(R+Z_0)^2}{2R+2Z_0} \tag{1}$$

where R – is the value of each resistor in the resistive splitter structure. To provide for an ideal match, $Z_{in} = Z_0$, which combined with (1) gives $R = Z_0/3$. It can also be shown that for the N-way resistive divider, the value of the resistor is given by the formula:

$$R = Z_0 \frac{N-1}{N+1} \tag{2}$$

When designing a resistive power divider in a three-dimensional electromagnetic modeler and simulator, special attention must be given to the junction at the center of the structure. This especially applies to high frequencies of millimeter waves where even small geometrical changes of order of 20μm may cause a significant impedance mismatch.

The Wilkinson power divider, shown in Fig. 2, 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 who invented it back in 1960s. The design of the Wilkinson divider 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. Based on the number of the quarter-wave sections, one can achieve good match at all ports in a desired frequency band. Resistors, connected at the junctions between individual 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. This causes the connecting resistors to have no voltage drop across them, and consequently, dissipate no power [2].

In even-mode analysis, two identical signals are applied to the two outputs of the Wilkinson splitter and the input is terminated to 50 Ω. Such an excitation produces a zero magnetic field 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 100 Ω to 50 Ω. The resistors, if assumed ideal and with zero electrical length, play no role in this impedance matching problem. In odd-mode analysis, two signals of identical amplitude and opposite phase are applied to the two outputs of the splitter. This excitation creates an electric wall (virtual ground) at the plane of symmetry of the splitter. Half of the structure is further analyzed with half of each resistor connected to the ground.

The T-junction at the input side where two branches merge into one is shorted. Since this T-junction is directly connected to the first quarter-wave section, the short will ideally transform into open. Hence, the odd-mode analysis turns into an impedance matching problem with multiple resistors and quarter-wave transforming sections between the resistors. Values of impedances and resistance values for different configurations is elaborated in detail in [4].

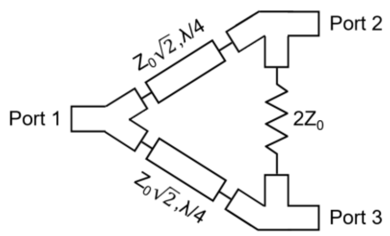

Fig.2. Basic structure of Wilkinson power splitter with equal power split ratio.

There have been many variations of Wilkinson splitters reported that target a specific goal such as broadened bandwidth, suppressed harmonics, low insertion loss, compactness, or low manufacturing cost. Ekinge [4] presented a method of synthesizing matched broadband power splitters with multiple coupled quarter-wave transforming sections and resistors. Deutschmann and Jacob [5] introduced a new type of ultrabroadband compact power dividers for the frequency range of 2 to 40 GHz. Demir et al. [6] proposed a model of efficient wideband power divider for planar antenna arrays that used Klopfenstein impedance taper for a significant reduction of the physical dimensions of the component. An extensive overview of different configurations and variations of Wilkinson power splitters can be found in [7].

IMPACT OF DIFFERENT MOUNTING OPTIONS ON ELECTRICAL PERFORMANCE

Power dividers may be realized on different planar platforms—microstrip, stripline, coplanar waveguide, etc. Each platform has its unique advantages and disadvantages. A microstrip platform provides for the simplest design and the most 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 divider 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. 3). In a flip chip configuration, the RF structure is in a direct contact with the application (test) board. This configuration provides for a good impedance match. However, the microstrip chip does not have a ground plane on the side opposite to the RF signal structure and 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 major 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 or the test 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. This is especially the case for the flip chip configuration that has no ground on the other side of the microstrip chip. Power dividers 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 divider on a different application board, the power divider probably will not be impedance-matched. This would result in significant reflections. Finally, both flip chip configurations suffer from the variable air gap between the microstrip chip and the application board. This air gap depends on the thickness of the metallized traces on both the chip and the board. As a significant amount of electromagnetic field runs through this air layer, a low dielectric constant of air compared to the permittivity of the dielectric substrates used will have a significant impact on the effective permittivity of the structure.

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 grounded plane connected to the board. The RF structure is electrically separated from the application board through the presence of the grounded plane on the bottom plane of the chip. Therefore, the electrical properties of the application board do not affect the performance of the power divider except in the localized areas of the contact pads through which the power divider 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 divider if a substrate with a high dielectric constant is used.

To compare the performance in different configurations, a few power dividers have been designed, manufactured, and tested. Board thickness, substrate (chip) thickness, and total thickness were measured using 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. 4) varies from 0 to 3 mil (0.076mm). This variation significantly affects the line impedances in the power divider structure. The air-filled gap between the chip and the application board caused by thicker-than-expected metal thickness adds undesirable inductive effect that affects VSWR and isolation.

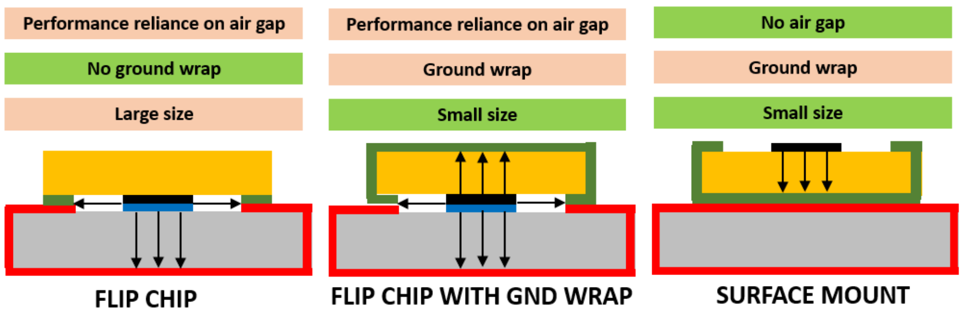

Fig. 3. Advantages and disadvantages of different mounting options.

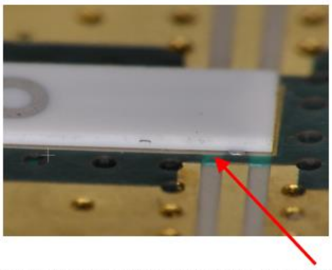

Fig. 4. Air gap between the microstrip chip (white) and application board (gold/green) that causes inductive mismatch.

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 as well as the variability of the air gap between the chip and the board.

RESISTIVE AND WILKINSON POWER DIVIDERS FOR MILLIMETER WAVES

To properly support the introduction of new technologies at frequencies of K band, Ku band, and further towards millimeter wave, all aspects of component design and development must be considered—this includes high-frequency fixturing, high-frequency probing, and production testing. With the operational frequency increase, sizes of surface-mount chip components shrink while DUT-to-test-board air gaps become more critical. This and similar dimensional constraints create significant issues for a production test technician and therefore require serious consideration and analysis.

The first step in properly mounting the DUT for testing is to carefully inspect all the components of the test fixture to be assembled. Special attention should be given to the test board edges (Fig. 5a). Common PCB manufacturing often leaves rough edges that can cause fixture assembly issues. The edges of the test board can usually be cleaned up using fine-grit sandpaper (Fig. 5b).

The next step is the fixture assembly; the carrier board is soldered to the test board using Sn96 solder. Care should be taken to ensure there is no solder run out into the area where the DUT is to be mounted. To complete the fixture assembly, the connector is mounted to the test board. It is important to center the connector pin on the transmission line and to confirm that the connector is flush with the edge of the test board to avoid undesired air gaps. Use of a microscope is essential to ensuring that the connector is mounted properly.

Now that there is a properly assembled test fixture, it is time to mount the DUT. The DUT should also be inspected to guarantee the edges are cleanly cut and are not jagged prior to being installed on the test fixture. Due to possible power-handling requirements, the DUT needs to be soldered in place. This presents challenges in proper alignment to the transmission line. When soldering, the DUT tends to move during solder reflow. To prevent this, pure indium solder could be used. The indium solder is very soft, and the DUT can be pressed into the solder before reflowing. This allows for fine adjustment of the DUT to the transmission line and ensures that the DUT is flush with the test board. When the DUT is reflowed, it remains in place. Finally, the DUT need to be connected to the transmission line. There are primarily two types of connection methods: ribbon bonding and wire bonding. Short ribbon bonds provide the best RF performance, but wire bonding is the most popular. In order to analyze the effects of the different connection methods, it is important to use the same DUT. This can prove difficult as removing the ribbon or wire bonds can often damage the circuit. In order to prevent any damage, the ribbon bond can be replaced with a small piece of indium solder. The indium solder does not need to be reflowed; it only needs to be pressed into place. The pliability of the indium allows for solid contact to the transmission line and DUT. It can then be easily removed and replaced with the wire bonds. This allows for a direct comparison of the effects of the different connection methods using the identical DUT and fixture. All satisfactory assembly practice plays an extremely important role at high frequencies. As the simulation analysis showed, small tolerances or changes in the shape and position of wire bonds can result in significant deterioration of electrical performance at high frequencies. Poor wire bond and other mounting practices (Fig. 6) result in significant reflections that "mask" the true performance of the DUT. Alternatively, proper installation (Fig. 7) results in a good correlation between the designer's simulation and the tested prototype.

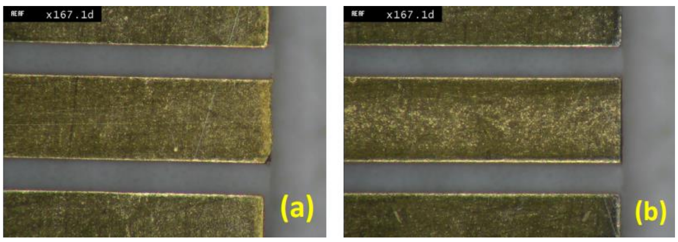

Fig. 5. Test board transmission line: (a) rough edge (before cleaning), (b) smooth edge (after cleaning).

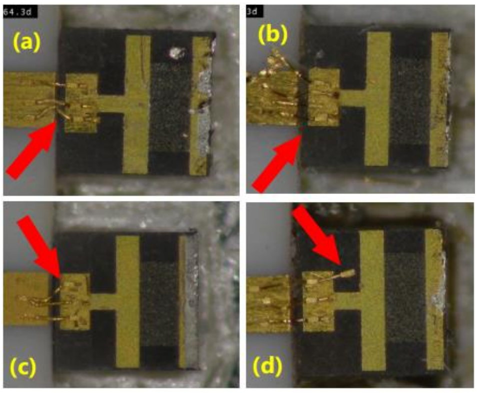

Fig. 6. Bad mounting practices: (a) poor wire bond connection to the pad, (b) air gap between the termination and the application board, (c) poor wire bond, (d) wire bond sticking out of the pad area.

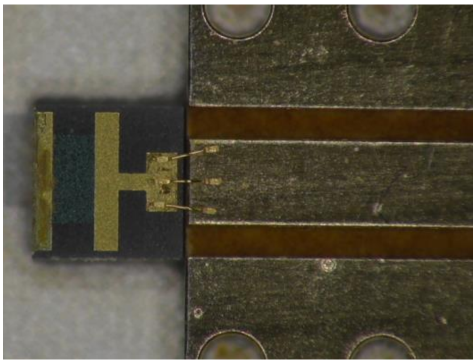

Fig. 7. Properly installed discrete RF chip on the application (test) board.

RESISTIVE AND WILKINSON POWER DIVIDERS FOR MILLIMETER WAVES

Designing a resistive or a Wilkinson power divider for millimeter waves has its own unique challenges. The physical length of the quarter-wave transformers is very short and often at the same order of scale as the corresponding line width at these incredibly high frequencies. The size of the resistive elements is electrically significant and introduces reflections that need to be properly tuned. Radiation effects become notable and must be properly addressed during the design of the power divider. Finally, even a small misalignment during the mounting of the divider onto the application board may result in a significant amplitude and phase imbalance. Nevertheless, surface-mount resistive and Wilkinson power dividers, if designed and mounted properly, provide for an excellent electrical performance and offer all the flexibility of a discrete component.

The resistive 2-way power divider (Fig. 8) is designed on a standard alumina platform and offers a broadband performance (Fig. 9) that covers the entire range of frequencies from DC all the way up to 40 GHz. This component is optimized for a miniature size of 1.52 mm × 1.27 mm × 0.25 mm. As observed in Fig. 10, insertion loss of the resistive power divider is slightly below -6 dB, which means that half of the power is dissipated in the structure as expected. The return loss is better than –20 dB over the entire broad range of frequencies up to 40 GHz.

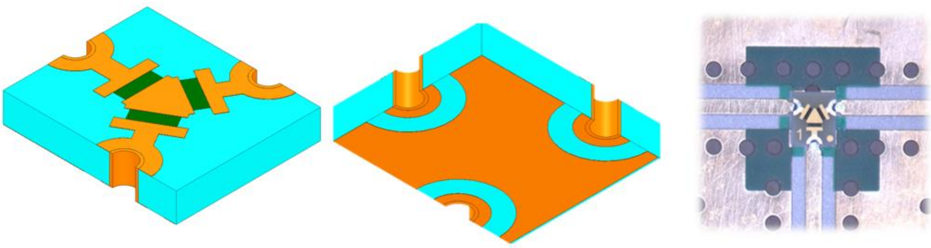

Fig. 8. Resistive power divider, DC–40 GHz: three-dimensional view (left), top view of the component mounted on the test board (right).

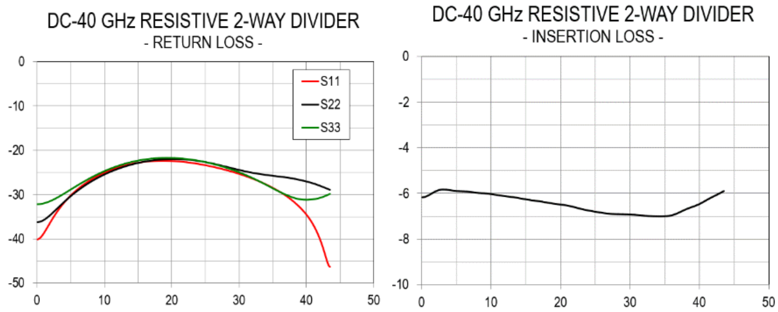

Fig. 9. Resistive power divider, DC–40 GHz, tested performance: frequency in GHz (x-axis), s-parameters in dB (y-axis).

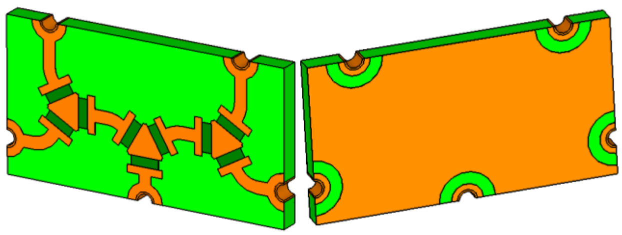

Fig. 10. Resistive 4-way power divider, DC–40 GHz: three-dimensional view from the top and the bottom.

Basic structure of a 2-way resistive divider can be expanded into more complex structures with a higher order power split ratio such as 4-way, 8-way, etc. The position of the ports is adjusted properly to create a compact 4-way design, as shown in Fig 10. It is possible to customize the design for a specific size and position of input and the outputs.

Wilkinson splitters exhibit better insertion loss performance than resistive power dividers. However, since this type of power splitter relies on the quarter-wave impedance transformation, it is inherently a narrowband structure. To validate the proposed design procedure based on even- and odd-mode analysis, a few 2-way Wilkinson splitters with equal split ratio at Ka-band frequencies (Figs. 11–14) are designed, manufactured, and tested. The splitters are characterized by –20 dB return loss, –20 dB isolation, and –0.5 dB insertion loss over the entire frequency bands of interest, 15–25 GHz and 25–35 GHz (Figs. 12 and 14). The shape of the power splitters may be properly adjusted accordingly by bending the quarter-wave sections. For example, the size of the power splitters (Figs. 11 and 13) has been reduced in an axial direction by bending one or both of the two quarter-wave transforming sections into a U-shaped structure. The size of these two discrete surface-mount components is 3.05 mm × 2.03 mm × 0.25 mm and 2.41 mm × 1.65 mm × 0.25 mm for 15–25 GHz and 25–35 GHz power splitters, respectively. Both splitters are realized on alumina substrate.

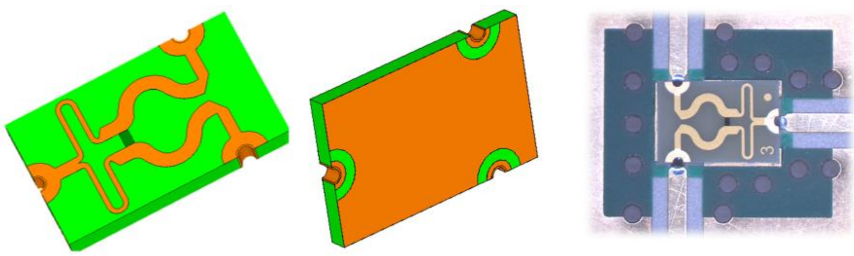

Fig. 11. Wilkinson 2-way power divider with equal split power ratio, 15–25 GHz: three-dimensional view (left), top view of the component mounted on the test board (right).

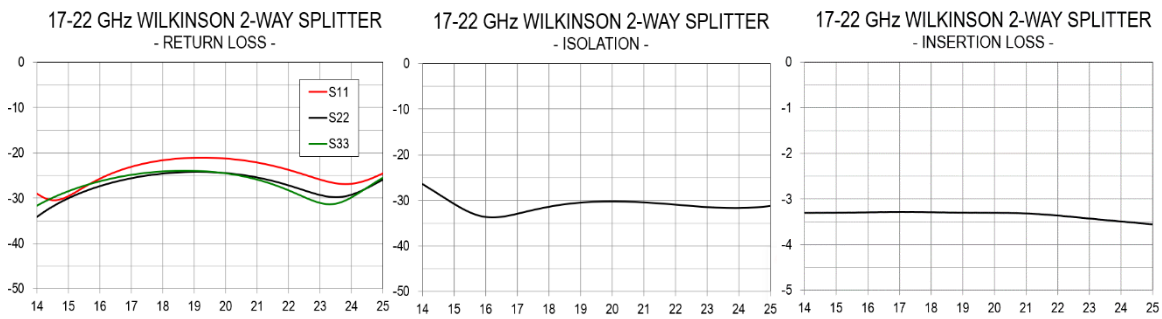

Fig. 14. Wilkinson 2-way power divider with equal split power ratio, 15–25 GHz, tested performance: frequency in GHz (x-axis), s-parameters in dB (y-axis).

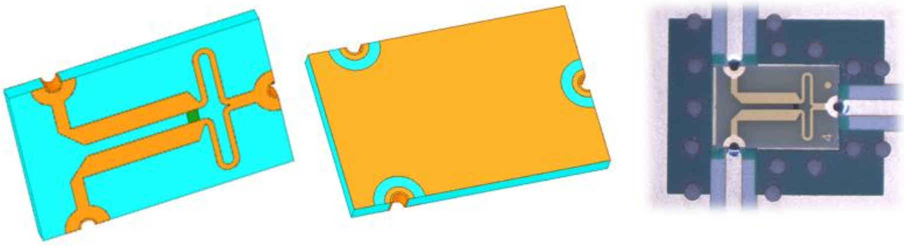

Fig. 13. Wilkinson 2-way power divider with equal split power ratio, 25–35 GHz: three-dimensional view (left), top view of the component mounted on the test board (right).

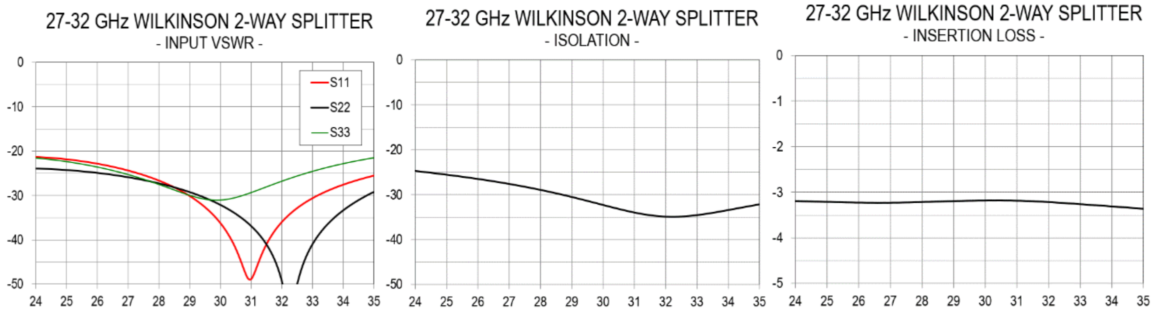

Fig. 14. Wilkinson 2-way power divider with equal split power ratio, 25–35 GHz, tested performance: frequency in GHz (x-axis), s-parameters in dB (y-axis).

The design of Wilkinson 2-way splitters with equal split ratio is based on: (1) even-mode and odd-mode analysis and (2) heavy reliance on the RF structure symmetries. For example, electric wall (E=0 plane, virtual ground) in odd mode and magnetic wall (H=0 plane) in even mode cut the splitter exactly in two identical halves. Hence, the entire simulation may be performed on a half of the splitter which significantly reduces the complexity of the simulated model and the required simulation time. On the other side, to design 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 a 3-way, 6-way, and others. A power splitter with an unequal power split ratio of 2:1 and the corresponding performance are shown in Figs. 15 and 16. The size of this discrete surface mount component is 4.44 mm × 2.16 mm × 0.25 mm and is realized on alumina substrate. Unequal power dividers are often used in the feeding networks for antenna arrays where their performance affects multiple antenna elements.

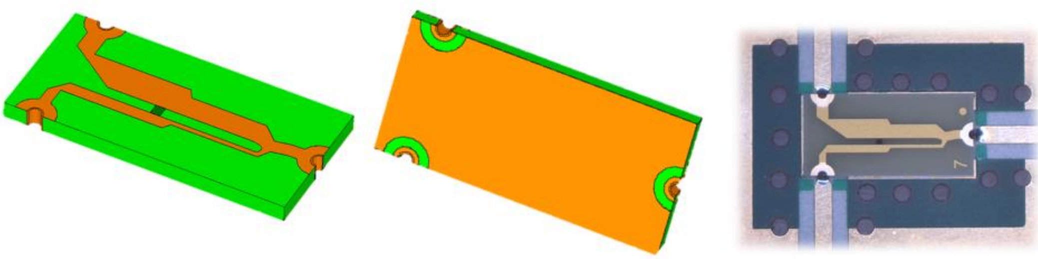

Fig. 15. Wilkinson 2-way power divider with unequal split power ratio, 15–25 GHz: three-dimensional view (left), top view of the component mounted on the test board (right).

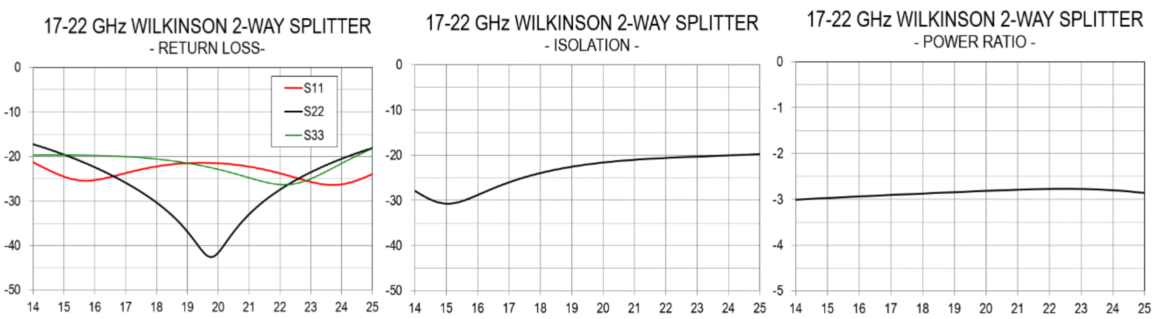

Fig. 16. Wilkinson 2-way power divider with unequal split power ratio, 15–25 GHz, tested performance: frequency in GHz (x-axis), s-parameters in dB (y-axis).

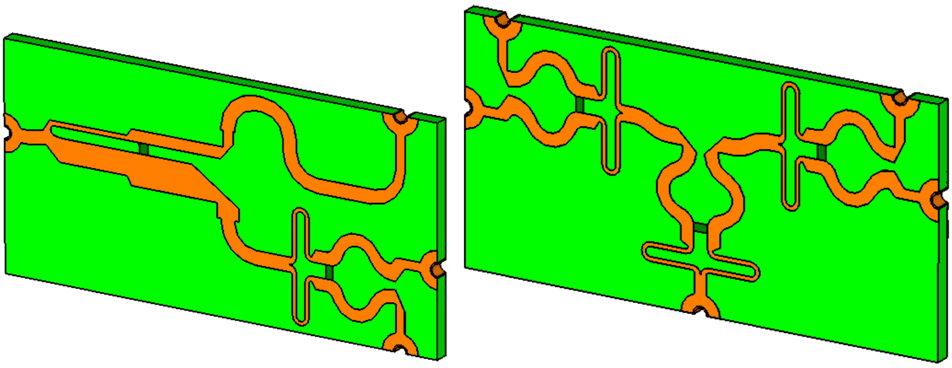

Fig. 17. Wilkinson power splitter with higher power split ratio: 3-way, 15–25 GHz (left), 4-way, 15–25 GHz (right).

The 2-way power splitters in both the equal split and unequal split power ratio shown in Figs. 8–16 are used as basic building blocks for more complex power splitters such as 3-way, 4-way, or 6-way. The position of the ports on the building blocks is properly adjusted. A few power splitters with higher power ratios are designed and manufactured and shown in Fig. 17.

WILKINSON DIVIDER IN SUSPENDED AIRLINE TECHNOLOGY

Modern radar and satellite systems often require a low insertion-loss performance of their integral parts to accommodate for a stringent loss budget and long communication paths. This restriction is imposed on the corresponding beamforming networks as well. To meet this design requirement, the beamformers are often realized in suspended airline technology (Fig. 18) that provides for a low effective-dielectric constant and consequently low insertion loss.

An important phase in the development of such a beamformer is the design of a corresponding Wilkinson power splitter [4]. If the splitter consists of coupled quarter-wave impedance transforming sections, then these sections would have different electrical lengths in even and odd modes due to different phase velocities of the two modes. This effect is further strengthened at the chip-resistor locations due to a high dielectric constant of the material the chips are built from (usually alumina, BeO, etc). Therefore, if the physical lengths of quarter-wave impedance transforming sections are tuned to be equal to quarter-wave lengths in even mode, the same physical lengths would not represent 90º sections in odd mode. They would most probably be longer than 90º due to a higher dielectric constant of odd mode. This creates a design obstacle that is very difficult to overcome and results in poor functionality of the corresponding splitter.

The problem of different lengths for even and odd modes has been treated by many authors in the past. March [8] used lumped elements to achieve phase-velocity compensation in the two modes while Podell [9] proposed 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 would not be suitable for a Wilkinson power splitter in suspended stripline, either because the solution would be too bulky or would not be compatible with the suspended stripline as a choice for the material platform.

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 [2], but instead pulled toward the T-junction (Figure 19a). In even mode (Fig. 19b), this technique would still result in a traditional multisection quarter-wave transforming network optimized through the use of Chebyshev polynomials [7]. In odd mode (Fig. 19c), however, each transmission line section between the two consecutive shunt resistors will consist of two elements with different characteristic impedances but their electrical lengths would add up to a total of 90º.

The values of the shunt resistors then need to be optimized to satisfy matching conditions in a newly arisen odd mode transforming network [12]. This optimization is accomplished through an algorithm developed for this purpose and tested through multiple examples.

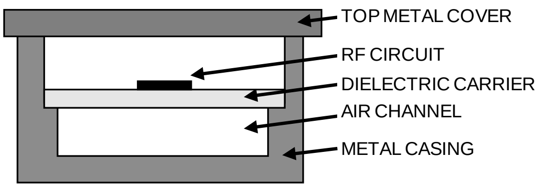

Fig. 18. Cross-section (stack-up) of an RF component realized in suspended airline technology.

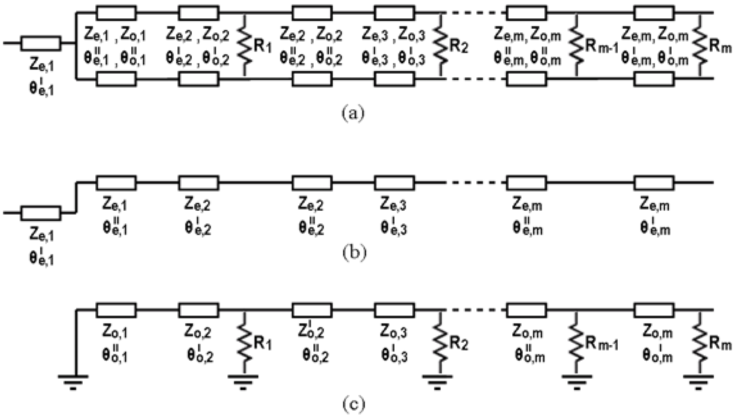

Fig. 19. (a) The transmission line model of the proposed power splitter, (b) The corresponding model in even mode, (c) The corresponding model in odd mode.

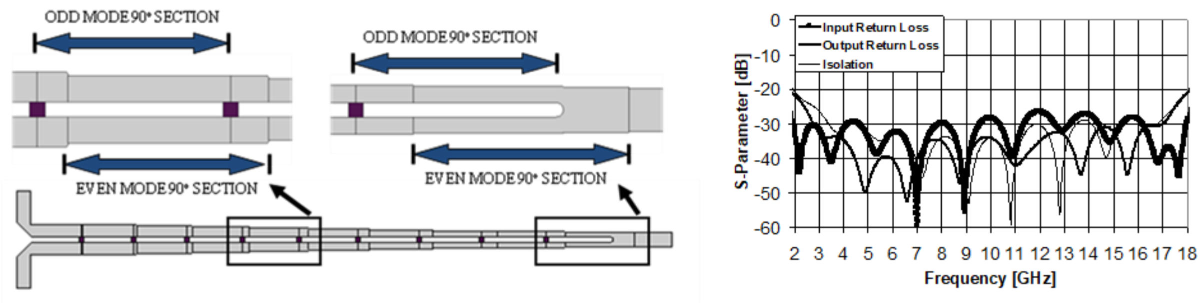

Fig. 20. 10-section 10-chip Wilkinson power splitter with tuned quarter-wave transformer lengths: geometry (left), performance (right).

A 10-section, 10-chip equal-split Wilkinson power splitter (Fig. 20) is developed using the proposed technique. For this design, we have used 0.125mm thick Taconic TLE-95 substrate as a dielectric carrier, with 0.625mm deep air channels on the top and bottom of the carrier (see Fig. 18). The geometry of the splitter with the clear indication of the impedance transformation location shift due to the previously described reasons is shown in Fig. 20.

CONCLUSION

Power splitters will continue to play a major role in the RF power distribution systems. A large variety of different 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. In this paper, we presented a series of surface-mount resistive and Wilkinson power splitters at millimeter wave frequencies that could be easily deployed in various RF beamforming systems. Advantages and disadvantages of various mounting platforms have also been discussed with the conclusion that the surface-mount option provides the superior performance compared to the alternatives. Finally, we proposed a design technique for Wilkinson power splitters in suspended airline technology that provides a low insertion loss and thus is attractive for space applications.

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AUTHORS

Mo Hasanovic received the M.S. and Ph.D. degrees in electrical engineering from Syracuse University, Syracuse, NY, in 2002 and 2005 respectively. He has been with Smiths Interconnect since 2012 filling various roles and responsibilities in the area of the new product design and development of board level RF components. His technical expertise is primarily in the passive RF component design for beamforming networks, radar systems, and other RF applications for commercial, military and space markets. His interests recently also include the integration of RF and photonics, specifically, RF over fiber devices. He authored or co-authored over 30 conference and journal articles and three textbooks in electrical engineering. Dr. Hasanovic is a member of IEEE, Optica, SPIE, and ACES.

Juan G. Ayala holds an Engineering degree from the Florida Institute of Technology with the Outstanding electronics student award in 1982. Juan has worked at Smiths Interconnect for 22 years in various roles in new product design and test and high reliability product compliance. His previous occupations include being an RF Design Engineer for Motorola Pagers and Cellular handsets, and as a Systems Design & Implementation Specialist for Whiticar Boatworks. Juan is an avid surfer, watch collector, and flute player.