Monolithic Low Cost Ka-Band Wilkinson Power Dividers on Flexible Organic Substrates

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Abstract

A millimeter wave Wilkinson power divider is presented on a thin and durable organic substrate, along with an analysis of bend topologies to reduce coupling between the output paths. The divider provides excellent performance across the entire Ka-band from 27 to 40 GHz. Insertion loss is approximately 0.3 dB and isolation between the output ports is around 30 dB at the design frequency.

Introduction

Power dividers are a primary building block of microwave communication systems. Stated simply, a power divider splits an input signal into two or more identical, potentially phase shifted, output signals. Often there is a desire to isolate the output ports so that reflected signals do not propagate to other paths of the system. An elegant solution to this problem is the Wilkinson power divider. Shown in Figure 1, the Wilkinson divider uses a resistor to isolate its two output ports, while maintaining a matched impedance at all ports [1]. When implemented in a planar format such as printed wiring boards, a common dilemma in Wilkinson power divider design lies in separating the quarter-wave transformer arms to prevent strong mutual coupling, yet keeping them close enough to place a resistor between them. At lower microwave frequencies, a simple U-shaped bend is sufficient to meet these objectives. Scaling such a design to millimeter wave frequencies introduces physical layout constraints that make a simple solution difficult to achieve.

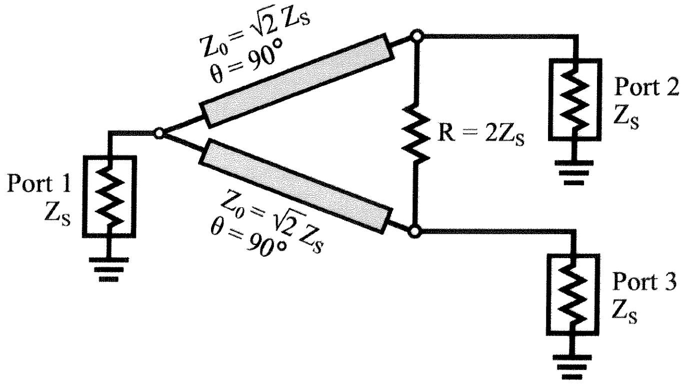

Figure 1. The Wilkinson power divider

These frequency scaling difficulties are caused by the properties of the microstrip transmission lines. The characteristic impedance of these lines are largely a function of the signal conductor width and the substrate height, while the electrical length, θ, is primarily dependent on the effective wavelength at the desired frequency of operation. Therefore, as frequency increases, the length of the quarter-wave transformers decreases, while the width remains relatively constant. When these lines include several 90 degree bends, creating the necessary layout without overlap or detrimental RF performance becomes increasingly difficult to achieve in the physical space available.

There are several ways to gain space for the transmission lines. One way is to reduce the thickness of the substrate. This will decrease the conductor width necessary to achieve a given characteristic impedance, but it will also add to the conductor losses present in the circuit. Another approach is to decrease the physical space required by the resistor. A separate packaged resistor component has traditionally been employed for Wilkinson divider designs. These packaged component form factors come in fixed sizes, add undesired parasitics at microwave frequencies, and restrict multilayer system integration. For these reasons, it is desirable to have an integrated resistor that can be scaled to be as large or as small as necessary.

Integrated resistors are typically implemented with either thick film or thin film processes. Thick film resistors are typically metal oxides applied using a screen printing technique [2]. This process tends to leave defects in the film that can lead to stability problems over time. Thin film processes use a variety of metal alloys usually deposited using a sputtering process under vacuum to produce a very uniform film on the order of a few thousand Angstroms. This method is preferred for microwave resistor applications, however, the vacuum requirement of the sputtering process limits the sputtered area, effectively increasing the per unit cost of implementing thin film resistors. An alternative to this approach involves the use of commercially available resistive foils [3]. These foils are half ounce copper sputtered with a Nickel Chromium alloy using a roll-to-roll sputtering technique, which significantly reduces the cost to the circuit manufacturer. This research examines the physical integration issues involved with using this technology in order to develop a Wilkinson power divider for millimeter wave systems.

Design Considerations

In order to get the best performance out of the traditional Wilkinson power divider design, we need to manage the tradeoff between circuit loss and matching. This involves making the substrate as thick as possible, while maintaining adequate isolation between the impedance transformers to prevent parasitics from degrading the circuit performance. For a design in Ka-band, the length of a quarter-wave transformer will be on the order of 1 to 2mm for the effective dielectric constant seen in most organic substrates. Therefore, a substrate could not be more than several hundred microns thick in order to keep the conductor width small enough to create a practical circuit layout.

Liquid Crystal Polymer (LCP) is an ideal material for this task. Available commercially in 2 and 4mil thicknesses, LCP is an organic polymer laminate well suited for packaging applications. LCP is also a natural choice for millimeter wave circuits because of its low loss (*tan* $\delta = 0.003$ at 40 GHz) and relatively low cost [4]. Given the standard thicknesses available, a Wilkinson design on 4mil thick LCP would be preferable to a design on 2mil LCP in order to improve the loss as long as a practical layout can be found. In order to determine if this is possible it is important to understand the integration issues involved.

The standard Wilkinson design places the resistor between the branches of the output ports to isolate any return signals between them. This differential placing makes the Wilkinson divider useful in creating baluns [5]. In the forward case, the divider operates by splitting the input signal with a simple T-style junction. Each path then travels through a $\lambda/4$ transformer with an impedance designed to step the signal up to twice the system impedance. This signal is then placed across a resistance of twice the system impedance through the superposition of odd and even modes. This halves the signal to the original system impedance with half of the original input power on each branch. In the reverse case, an incoming signal on an output port will be presented with a $\lambda/4$ transformer and a resistor with twice the system impedance. In the odd mode the transformer will appear open and the resistor will be halved to the system impedance due to the virtual short created by the symmetry. In the even mode, the resistor is effectively eliminated from the circuit by the virtual open, while the $\lambda/4$ transformer presents the system impedance from the symmetrically doubled input port. Summing the two modes together we see that in an ideal case the incoming signal on an output port will be terminated with the system impedance with no reflections.

When looking to apply this design in a practical situation, it is important to consider the limitations of the technology used. In this case, the foils selected to reduce the cost of producing integrated resistors will also introduce several layout constraints. Since the thin film resistors are far too thin to be handled by themselves, they depend on the ½ oz. copper foil backing for support before lamination. The minimum feature sizes of the circuit will be dependent on the thickness of this foil, which also serves as the conductive layer. Using the standard ½ oz. copper foil, the minimum feature size was determined experimentally to be 75μm for traces and 50μm for slots. While smaller features were possible, these were determined to be the smallest features that could be reproduced accurately. When laminating to LCP, it was discovered that attempts to strip the copper foil and redeposit a thinner metal layer failed as the bonds between the LCP and resistor foil prevented good quality etching of the resistor material.

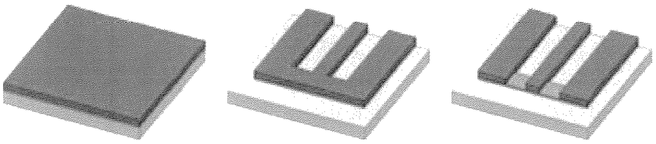
(A) (B) (C)

Figure 2. Foil transfer process etching steps

The etching process for forming the resistors after lamination can be seen in Figure 2. In part A, the sample is shown with the integrated resistor foil bonded to the LCP. After defining a pattern with a photoresist mask, the copper and thin film resistor lying underneath the copper can be etched in a single bath as seen in Figure 2B. A second photoresist mask followed by a selective copper etch exposes the thin film resistors and completes the formation of the layer. Like all wet etch processing, the etch profile is very close to isotropic. In the case of the 18μm thick ½ oz. copper foils, the resulting undercut can be very significant. In order to correct this phenomenon, an offset is required in the mask in order to produce the correct size features on the sample. The added size reduces the feature sizes and density capable in the design.

Also, depending on the etchant used in the first etch that removes both copper and resistor materials, the etch rate for both materials will not be the same, resulting in a resistor "ring" region where the unused resistor material will stick out from the conductor, shown most visibly in Figure 3A. The lines shown in Figure 3A were etched with cupric chloride, and leave a large ring around the conductor, while the lines etched with ferric chloride in Figure 3B show significantly less of the protruding resistor material. This excess material will not affect the electrical performance of the line, however, it will place additional restrictions on the line spacing capable using the fabrication process.

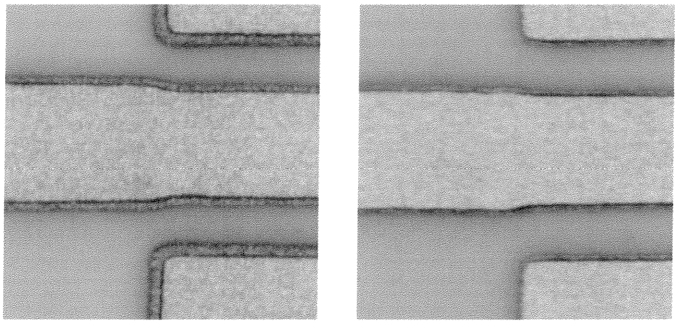
(A) Cupric Chloride Etch (B) Ferric Chloride Etch

Figure 3. Two different etchants used as the first etch

One final consideration is the accuracy of the resistor. Integrated resistors are only as good as the fabrication tolerance with which they can be created. Since resistance is highly dependent on physical dimensions, uniformity in length, width, and thickness need to be tightly controlled. Using the integrated foil eliminates the most difficult aspect to control, the thickness of the deposited thin film, leaving only the length and width of the resistor defined by the etching process. Accuracy of the thin film deposition is stated to be within 5% of the listed value, meaning any deviations in length and width will degrade the tolerance from that point. With mask adjustments to correct the etching undercut described earlier, resistance values can be kept accurate to within 10% as long as the resistor dimensions are kept greater than 100μm in both length and width.

Combining these constraints together, several designs were simulated using the general topology seen in Figure 4.

Starting with a 25Ω/□ resistor foil, the resistor was made as small as possible to meet the 100Ω resistor required by the divider. This gave the resistor a 4 to 1 ratio with dimensions of 400μm in length by 100μm in width. The quarter-wave transformers were then wrapped around the resistor in a semi-circular fashion. Numerical field solver simulations revealed that the best configuration using the maximally compact topology shown was achieved by making the bend radius as large as possible without impeding on the 50Ω lines needed for the output ports. Finally, the output and input line lengths were set to give an arbitrarily determined phase shift at the output. In this case, a 180 degree shift at 35 GHz was selected as a reference point.

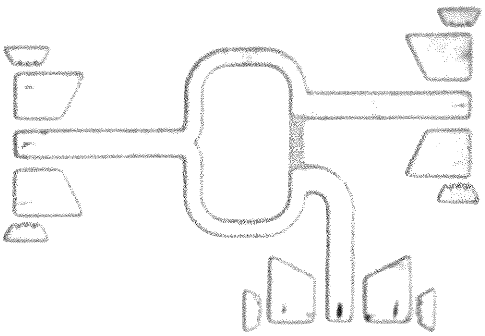

Figure 4. Fabricated Wilkinson power divider

Disregarding the CPW to microstrip transitions present in Figure 4, the circuit measures approximately 1.99mm in width by 1.63mm in height. This is significantly smaller than the divider presented by Antsos, which measures over 3mm by 6mm [7]. The increased size was necessitated by the thicker 15mil substrate and lumped resistor used in the design. The increased thickness makes a λ/4 transformer impossible to implement effectively, dictating the periodic increase to a 3λ/4 transformer. The advances in millimeter wave dielectric materials and integration processes over the last ten years have made this design possible at this frequency range.

Measurement and Performance

Measurements of the Wilkinson divider were taken using a four port Agilent 8364B PNA. An LRRM calibration using a Picoprobe calibration substrate was used to capture probed measurements. Figure 5 shows the insertion loss through the power divider. Designed for an equal power split that will ideally reduce each branch by 3dB, this design is showing slightly less than 0.5dB loss throughout Ka-band, from 27 to 40 GHz. Return loss for each port, shown in Figure 6, stays below 20 dB with the exception of the input port at the fringes of the band. Isolation between the output ports, shown in Figure 7, is on par with the return loss measurements. An analysis of the phase through each branch of the divider shows a constant shift of 2.5 degrees from the designed reference.

The jagged appearance of the return loss and isolation at low magnitudes are a result of the CPW to microstrip transitions used. A vialess transition was used in order to simplify fabrication [8]. The transitions maintain a very low insertion loss, but reduce the dynamic range of the PNA to a value typically around 35dB. The measurements obtained are an expected improvement over the design published in [6] simply because the improved technology for millimeter wave circuit integration allows for the same compact design at Ka-band that was previously only physically possible at lower RF frequencies.

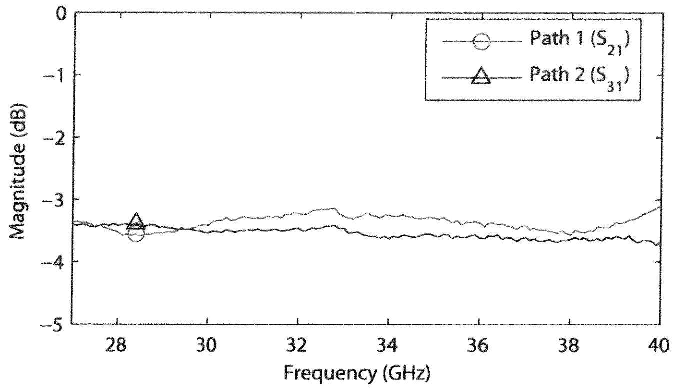

Figure 5. Insertion loss measurements

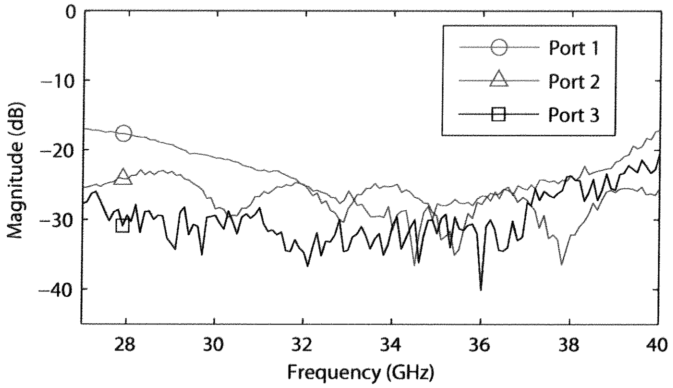

Figure 6. Return loss measurements

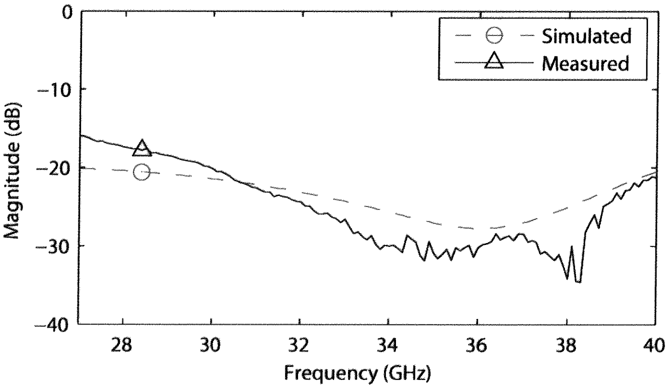

Figure 7. Isolation measurements between output ports

Conclusions

A Wilkinson power divider using low cost fabrication techniques has been demonstrated at millimeter wave frequencies. The circuit performance meets or exceeds that of previously published work in this band to the best of our knowledge. By keeping manufacturing costs low, this research hopes to make millimeter wave circuits a commercially viable option for the communication needs of the future.

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