Microwave Power Dividers and Couplers Tutorial

Overview and Definition of Terms

Power dividers and couplers are straightforward passive components. It is the attention to design detail, execution of the design, and quality of the fabrication which leads to a high performance component. In this tutorial, we present a basic overview of Marki Microwave power dividers and couplers, and define power divider and coupler terminology.

Section 1. Overview

The splitting and recombining of electromagnetic signals is a fundamental signal processing functionality in electronics. Many circuits exist in the RF and microwave designer's toolbox to facilitate effective signal splitting and recombination. The proper choice of circuit depends on the application and requirements; many engineers become confused due to the multitude of options available. This tutorial serves as a reference to help clarify the broad and sometimes confusing world of microwave power dividers and couplers.

Currently, Marki Microwave offers the following types of power dividers and couplers: *Resistive* power dividers (Fig. 1), *Wilkinson* power dividers (Fig. 2), *Directional* couplers (Fig. 3), and *Quadrature Hybrid* couplers (Fig. 4). Table 1 summarizes the typical attributes of these four categories and the range of performance currently offered by Marki Microwave designs. All power dividers and couplers split/combine[1] electromagnetic signals. The key difference between the various circuits is *how* the signal is split, and more importantly, *what* the resultant output signals look like in terms of amplitude and phase.

A. Power Dividers

In most circumstances, power dividers provide equal amplitude and equal phase splitting, as is depicted in Figs. 1 and 2. Notice that for both power dividers, the input signal at port 1 splits equally between output ports 2 and 3. In a resistive power divider, both output signals are 6 dB lower than the input signal, and they are in phase. In Wilkinson power dividers, the output signals are 3 dB below the input signal, and they are also in phase (i.e. 0 degree phase shift between the outputs). The extra 3 dB of path loss in the resistive divider is caused by the extra voltage drops across the 16.7Ω resistors. The main differences between resistive power dividers and Wilkinson power dividers are that Wilkinson power dividers have 3 dB lower loss and possess the advantage of *isolation* between output

[1]Many vendors will specifically use the terminology "power divider/combiner" to avoid confusion. We will drop the "combiner" label for simplicity—it is assumed that all power dividers are reciprocal, unless otherwise stated. Interestingly, Nature tends to make it very difficult to create non-reciprocal circuits. One of the only methods to make non-reciprocal passive circuits is to use magnetic materials. The Faraday Effect, for example, is commonly used to make non-reciprocal components like circulators and isolators.

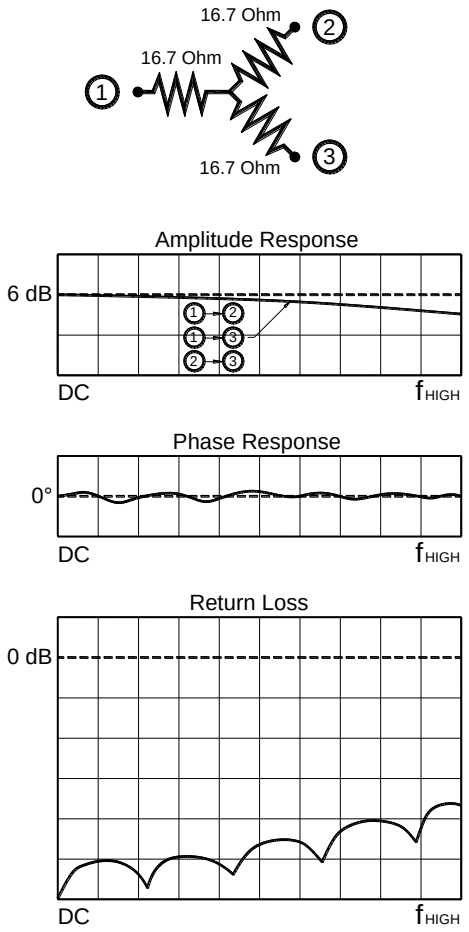

Fig.1. Resistive power divider circuit diagram, amplitude response, phase response, and return loss. Note that $S_{12}=S_{13}=S_{23}$.

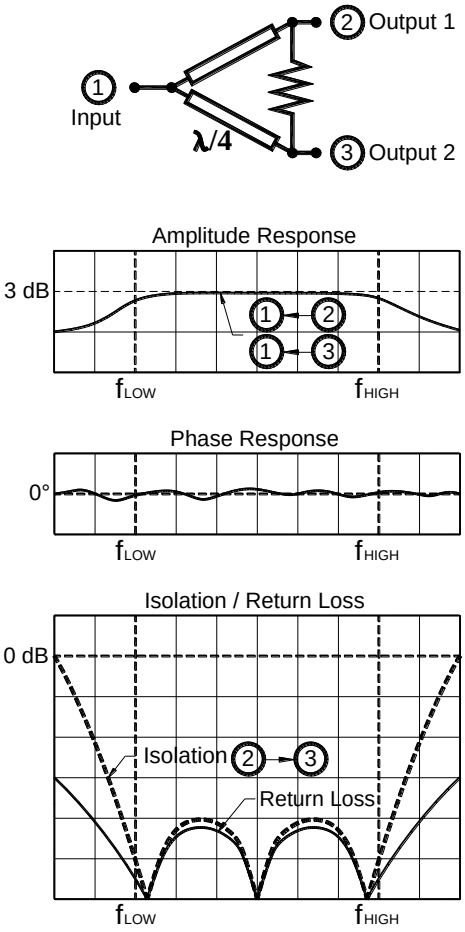

Fig.2. Wilkinson power divider circuit diagram, amplitude response, phase response, and isolation/return loss. Note the isolation between ports 2 and 3.

ports (see Fig. 2). Practically speaking, Wilkinson power dividers are limited in their low frequency range (f_{LOW}) to a few hundred MHz while resistive power dividers reach to DC.

Coupler

A key difference between couplers and power dividers is that couplers create a phase shift between the output signals. The main difference between directional couplers and quadrature hybrids is that directional couplers provide non-equal power splitting of the incoming signal (Fig. 3), while quadrature hybrids have equal (3 dB) power splitting (Fig. 4). Like Wilkinson power dividers, couplers are band limited and are always characterized by a low frequency (f_{LOW}) and high frequency (f_{HIGH}) of operation. The main application of a directional coupler is to pick off a small portion (somewhere between 0.1% and 25%, typically) of the signal on a transmission line such that the incoming power can be actively monitored without too much loss. Since directional couplers are most often used in power sensing

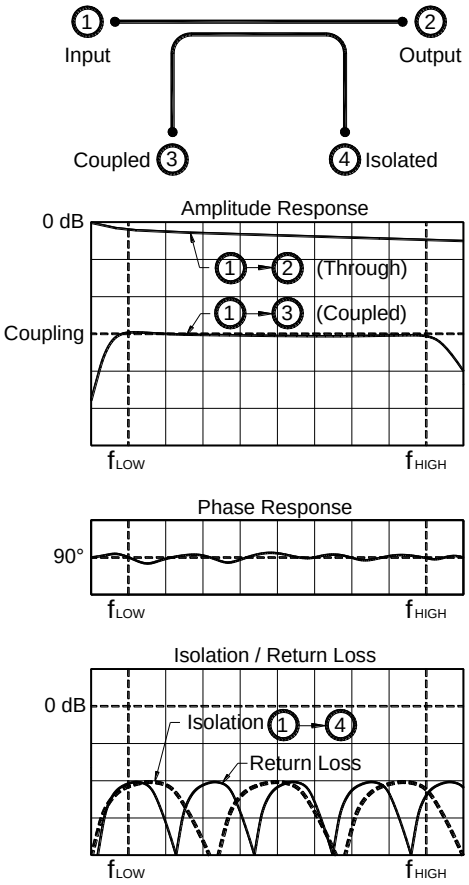

Fig.3. Directional Coupler circuit diagram, amplitude response, phase response, and isolation/return loss.

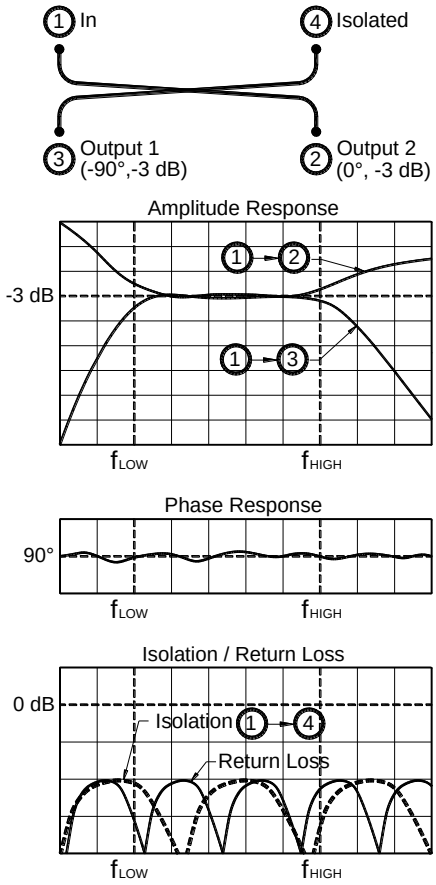

Fig.4. Quad Hybrid Coupler circuit diagram, amplitude response, phase response, and isolation/return loss.

applications, their phase information is usually not specified. In contrast, the 90 degree phasing of quadrature hybrid couplers (Fig. 4) is *always* specified since the phase accuracy is critically important for many applications like IQ-modulation and demodulation, single-sideband up-conversion, and image reject down-conversion. In both directional couplers and quadrature hybrids, the best performance is obtained when the circuits are well matched to 50 Ω. It is common for Marki Microwave couplers to obtain return loss values on the order of 25-30 dB, with isolations in excess of 30 dB. This performance is achieved through precision coaxial-to-stripline transitions and a proprietary optimization algorithm.

Section 2. Figures of Merit

Generally, power dividers and couplers are quantified using nearly identical figures of merit, with a few subtle differences. The following list details the various metrics and some of the nuances that are often encountered when designing and specifying performance in datasheets.

A. Splitting Ratio/Coupling Ratio

Splitting ratio (a.k.a. coupling ratio) is defined as the ratio of output power to input power. By convention, the amplitude ratio is defined by the lower of the two output powers. Thus, a 90:10 split would imply a coupling ratio of 10 dB and a 99:1 split would imply a coupling ratio of 20 dB. Typically power dividers are designed such that the input power is equally distributed among the output ports. Thus, a 2 to 1 power divider passes 50% (-3 dB) of the power to each output. A 3 to 1 power divider passes 33% (-4.8 dB) of the power to each port, and so on.

Directional couplers are best suited for applications requiring unequal splitting ratios. While it is theoretically possible to create Wilkinson power dividers with unequal splitting ratios (a.k.a. "asymmetric" Wilkinsons), it is uncommon to do so because of unrealizable fabrication tolerances.

Various resistive circuits called pick-off tees, resistive taps, and resistive couplers exist that also generate unequal power splitting. Such circuits are simple voltage dividers and are similar in operation to the 6 dB resistive power divider in Fig. 1. Advantages of these circuits are size and bandwidth. Disadvantages are increased insertion loss and low isolation, which can lead to crosstalk between output channels.

B. Relative Phase Shift

Various power divider and coupler circuits exist which facilitate either 0 degree (in phase), 90 degree (quadrature phase), or 180 degree (differential) phase shift between the two output signals. Generally, 0^{o} (in phase) circuits are the easiest to design, followed by the 90^{o} and 180^{o} circuits. Splitters that yield differential outputs are often called Magic-T's. Examples of Magic-T circuits are the rat-race coupler, the asymmetric tandem coupler, and the parallel coupled line Magic-T. Currently, Marki Microwave offers 180 degree hybrid couplers as custom designs only. Contact the factory for more information regarding these custom components.

A final class of splitters exists called Baluns. Baluns are unbalanced to balanced transformers that provide a 180 degree phase shift between the two output ports. *The primary distinction between a Balun and a Magic-T is that Baluns are 3 port circuits that do not provide isolation between outputs. The Magic-T is necessarily a 4 port circuit and always provides isolation between outputs*. Baluns are critical building blocks for mixers and balanced amplifiers. Currently, Marki Microwave offers a class of ultra-broadband Baluns that operate from 200 kHz to beyond 6 GHz. These broadband Baluns are ideal for use with high speed Analog to Digital converters.

C. Amplitude Balance

Amplitude balance is a measure of how evenly the power is split between the two arms of the device, and it is not applicable to directional couplers because they have an uneven power ratio. The amplitude balance is typically less than 0.25 dB for Marki power dividers and 0.4 dB for quad hybrid couplers.

D. Amplitude Ripple

Amplitude flatness is determined by how well the divider maintains the

amplitude ratio over a specified bandwidth. Ideally the device would provide a perfectly flat (i.e. 0 dB) ripple over the usable bandwidth. However, this is never the case and real devices will have some amount of amplitude ripple around the nominal splitting ratio. Typical values range from a few hundredths of a dB to over 1 dB depending on the design. **In many designs, amplitude flatness can be traded for bandwidth**. Hence, a 2-8 GHz device might specify a very flat 0.3 dB ripple while a 2-18 GHz device might specify a 0.7 dB ripple. Acceptable levels of amplitude ripple are application specific. Power dividers have better amplitude flatness than couplers, as a general rule.

E. Phase Balance

Phase balance is a measure of the differential phase shift between the two output arms. Like Amplitude Balance, Phase Balance primarily applies to equal output power components like Wilkinson power dividers and quadrature hybrids. Most components provide a phase balance of a few degrees, and this balance tends to get worse at higher frequencies.

F. Phase Ripple

Like amplitude flatness, phase flatness corresponds to how well the constant relative phase shift is maintained throughout the bandwidth of the device. Well designed and packaged power dividers and couplers will fluctuate by only a few degrees over the entire usable bandwidth. Usually, the higher the operating frequency, the more difficult it is to maintain constant phase flatness. Phase error is mostly caused by small transmission line length asymmetries between the two output ports. This problem is exacerbated when there is poor VSWR matching at the ports. Careful design and packaging techniques help to maintain accurate phase flatness.

E. Insertion Loss

For power dividers and couplers, insertion loss refers to the **additional** loss above the nominal loss due to splitting. For example, in a 3 dB power divider the insertion loss might be specified as 0.5 dB. This implies that for a 0 dBm input signal, the two output signals will be approximately -3.5 dBm each. The additional losses are caused primarily by reflections, dielectric absorption, radiation effects, and conductor losses. Broadband designs tend to have higher insertion losses because they are physically longer devices, and thus accumulate more dielectric, radiation, and conductor losses. Conductor losses in high frequency devices are caused predominantly by the skin effect and the surface roughness of PCB traces. Losses caused by reflections also increase with increasing frequency.

G. Power Divider Isolation

In an ideal power divider the output ports are mutually isolated. In other words, a signal entering output 2 does not leak out of output 3. Isolation is defined as the ratio of a signal entering output #1 that is measured at output #2, *assuming all ports are impedance matched (usually 50 Ω)*. Isolation values above 15 dB are considered good, and some designs are better than others in terms of achievable isolation. A common engineering trade-off tends to exist in power dividers and couplers: the larger the bandwidth and the higher the frequency, the more difficult it is to provide good isolation. Resistive power dividers, for

example, can achieve outstanding DC to 40 GHz coverage, but only provide 6 dB of isolation. A Wilkinson power divider, on the other hand, can achieve isolations better than 20 dB, but is impractical to build with bandwidths ratios greater than about 65:1.

H. Coupler Isolation and Directivity

Coupler isolation is different from power divider isolation because the coupler is a four port device. Coupler isolation measures the ratio between input power and power leakage from the isolated port. Typical values are 30-40 dB depending on the bandwidth of the device and the coupling ratio. To fairly measure the isolation of directional couplers with varying coupling ratios, another figure of merit called *directivity* is used. This is the ratio of coupled output power to leaked power from the isolated port, and can be calculated as the isolation in dB minus the sum of the coupling ratio and insertion loss:

$$\text{Directivity (dB)} = \text{ISO} - (\text{CPL} + \text{IL}) \qquad (1)$$

In the above equation, all units are in dB. As an example, a 20 dB coupler might have an isolation of 40 dB and an insertion loss of 0.04 dB. Therefore, the directivity is calculated to be 19.96 dB.

Directivity is an important figure of merit because it measures the ability of a directional coupler to distinguish between signals traveling in opposite directions. The higher the directivity, the better the coupler can distinguish between forward traveling and backward traveling waves. Referring to Fig. 3, this implies that in an ideal coupler port 3 will only see signals entering port 1 (the forward going wave), and will never see signals that enter from port 2 (the backward going wave). Any signal that enters port 2 and exits port 3 is considered a degradation in the directivity of the coupler.

In test setups where we are interested in measuring reflections from a device under test, the directivity of the coupler establishes the uncertainty of the measurement. As with isolation, directivity is bandwidth dependent; narrow band couplers tend to have better directivity than broad band couplers. At Marki Microwave, we optimize coupler directivity using modern numerical techniques to ensure state-of-the-art performance from a few hundred MHz to over 50 GHz. Our optimization techniques improve directivity by more than 10 dB for most designs.

I. VSWR/Return Loss

The metrics “voltage standing wave ratio” (VSWR) and return loss answer the same question: how well is the RF network matched to a given load and source impedance? Unless otherwise stated, all Marki Microwave components are designed to operate in 50 Ω systems. For power dividers and couplers, one must work very hard to maintain a good 50 Ω match over all frequencies to achieve the best performance, and to minimize reflections within the system. In fact, attributes like isolation and directivity are intimately related to the non-ideal 50 Ω nature of the power divider or coupler. When building very high directivity directional couplers, for example, we work diligently to guarantee that the transmission lines are precisely maintained to 50 Ω, and that any errors caused by line discontinuities are minimized. In general, one cannot have good isolation/directivity without also having excellent return loss performance.

Section 3. Summary

Given the above figures of merit, the ideal power divider would exhibit constant, flat amplitude splitting with constant, flat phase, minimal insertion loss and high isolation between output ports (at all frequencies and in a tiny package). As it happens, achieving all these goals in a single design is impossible. The art of power divider and coupler design often involves trading one or more of the above metrics for another. For example, achieving a large bandwidth with excellent isolation is (almost) always accompanied by increases in circuit loss and overall size. Contrastingly, extremely broadband devices can be made in very small packages (e.g. resistive power dividers), but only at the expense of insertion loss and isolation. Appropriate tradeoffs can be made only once the end-user goals are defined.

Table 1. Overview of Power Divider and Coupler Product Lines

	Resistive Power Divider	Wilkinson Power Divider	Directional Coupler	Quadrature Hybrid
Physics of Operation	Resistive voltage divider circuit	Quarter-wave transformer separates even and odd mode signals with an isolation resistor	Weakly coupled quarter-wave transmission line sections	Strongly coupled quarter-wave transmission line sections
Low Frequency Range	DC	100s of MHz	100s of MHz	100s of MHz
High Frequency Range	10s of GHz	10s of GHz	10s of GHz	10s of GHz
Maximum Practical Bandwidth Ratios	Operates to DC	65:1	65:1	13:1
Insertion Loss (Nominal)	6 dB (assuming 2 outputs)	10 log (N) (where N = # of outputs)	10 log (1/ (1-$10^{(CPL/10)}$))	3 dB
Coupling Ratio	Equal Power (6 dB)	Equal Power (3dB)	6 dB to 30 dB	Equal Power (3dB)
Isolation	6 dB	20 dB (typical)	30 dB to 40 dB	20 dB (typical)
Directivity	NA	NA	20 dB (typical)	NA
Phase Shift @ Outputs	0^o (In Phase)	0^o (In Phase)	90^o (usually not specified)	90^o

Section 4. Recommended Reading

1. ***RF and Microwave Coupled-Line Circuits*** **by Mongia, Bahl and Bhartia.**

Summary: In our opinion, the single greatest text for couplers and baluns! The book serves as an excellent resource for theoretical background and practical design implementation. The authors reference all the important publications and provide many useful examples.

2. ***Microwave Filters, Impedance-Matching Networks, and Coupling Structures*** **by Matthaei, Jones and Young.**

Summary: A classic in Microwave Engineering! A must have for any RF/Microwave engineer.

3. ***Nonuniform Line Microstrip Directional Couplers and Filters*** **by Sener Uysal.**

Summary: Based on the author's graduate work at King's College London, this text is a rigorous treatment of microstrip directional couplers. The author provides numerous examples and calculations to highlight the synthesis process. The design procedure is highly non-trivial, but the approach is novel and promising for low cost microstrip solutions.

4. ***Theory and Tables of Optimum Symmetrical TEM-Mode Coupled Transmission-Line Directional Couplers*** **by Cristal and Young**

Summary: A seminal work in multi-section coupler design. A must-read for those interested in broadband couplers.

5. **The Design and Construction of Broadband, High-Directivity, 90-Degree Couplers Using Nonuniform Line Techniques by Carl Tresselt**

Summary: A straightforward technique for designing tapered couplers. To see a design example, see Mongia's text (Chapter 7).

6. ***The Design of Discrete N-Section and Continuously Tapered Symmetrical Microwave TEM Directional Couplers*** **by David W. Kammler**

Summary: A rigorous and complete treatment for a novel technique to designing broadband tapered couplers. The fact that Kammler completed this work in 1969, long before the era of the personal computer and MATLAB, makes this work even more impressive.

7. ***Tables for Asymmetric Chebyshev High-Pass TEM-Mode Directional Couplers*** **by Fritz Arndt**

Summary: Provides useful design tables for asymmetrical tapers, which are a fundamental building block in broadband Magic-T circuits.

8. ***An N-Way Hybrid Power Divider*** **by Ernest Wilkinson**

Summary: The original paper by Wilkinson.

9. ***A Class of Broadband Three-Port TEM-Mode Hybrids*** ***by Seymour Cohn***

Summary: This paper describes multi-section Wilkinson power dividers. The author provides a theoretical framework for these circuits, and offers some useful design tables.

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