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Understanding the Magic Tee 0º Hybrid Combiner/Divider

A tutorial review of a classic RF circuit that is an essential component in many applications

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Combining and dividing RF signals is a common function required in power amplifiers, test and measurement systems, antenna systems and many other applications. An important device for this task when the operating frequency is in the 100s of MHz or below is the zero-degree or *magic tee* hybrid. The basic circuit is shown in Figure 1. The two circuit layouts are equivalent.

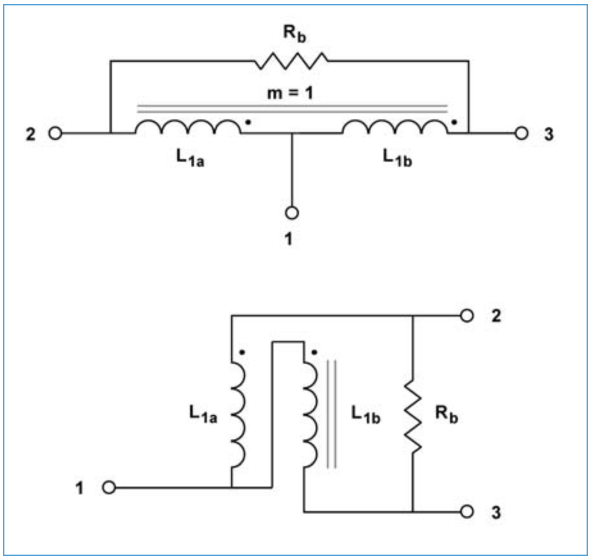

FIGURE 1
Two equivalent methods of depicting the 0º hybrid combiner/ divider. The top version shows the form from which the name "magic tee" arose, while the bottom layout more closely resembles the physical construction of a the inductor windings.

Desired Combiner/Divider Properties

What we want is a three-port device, a circuit that sums two inputs into a single output, or in the opposite direction splits a single input into two outputs. In this case, the two combined or divided ports will have equal amplitude, in-phase signals. Generally, it is useful if these two ports have significant isolation between them to minimize interaction between the two signal paths.

The final characteristic we will want in our divider is performance over the frequency span required for our application. This will be discusses after examining the topology and basic operation of the magic tee.

To avoid cumbersome language, in this article I will discuss the circuit as a divider, with a single "input" and two "outputs." The magic tee is a passive circuit, so it has reciprocal properties. Thus, the two ports referred to as outputs may also be inputs, which are summed into a single output.

The Wilkinson Divider

It is useful to begin the analysis with a review of the Wilkinson power divider, which uses quarter-wavelength transmission lines in the arms of the "tee" as shown in Figure 2. One purpose of the transmission line sections is to provide impedance matching. When the $\lambda/4$ lines have a characteristic impedance of $Z_0/\sqrt{2}$ they will transform the impedance by a factor of two, e.g., each of the two Z_0 outputs will appear as $2Z_0$ at the summing point, where the parallel combination results in simply Z_0 at the input.

The lines also create the desired isolation. In the top diagram of Fig. 2, we can see that the total line length between the two output ports is $\lambda/2$ or 180 degrees. The common mode (0º) signal is the desired output at the two ports, while any differential mode (180º) unwanted signals will have voltages canceled by the $\lambda/2$ delay.

The resistor across the two divided outputs

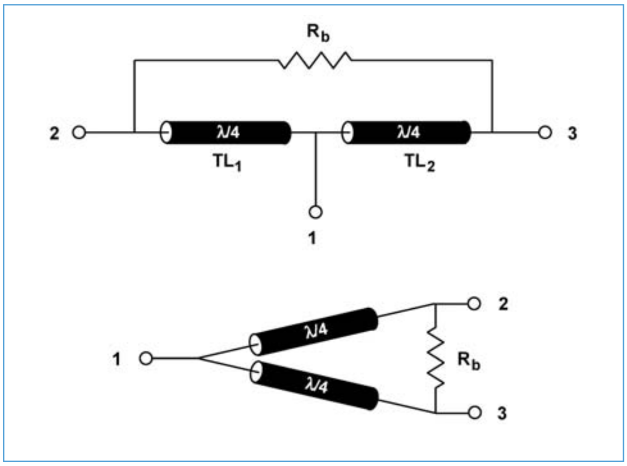

FIGURE 2

The Wilkinson divider circuit. As in Fig. 1, the top diagram is in the form of a tee, while the bottom diagram more closely resembles the physical construction, which typically locates the two outputs and the balancing resistor adjacent to one another.

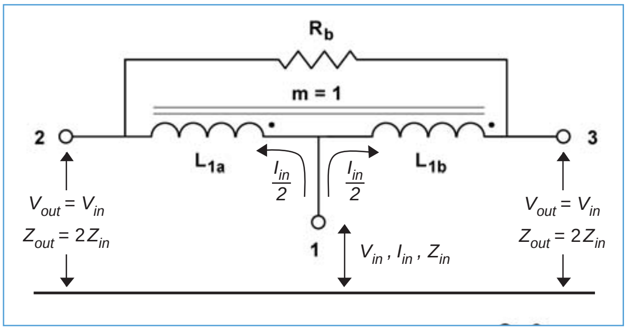

FIGURE 3

Voltage, currents and impedances of the magic tee hybrid. Note that the output impedances are twice the value of the input impedance. The two inductors share a single ferrite core, which increases the inductance and maintains mutual coupling near unity.

serves to absorb any differential mode signal leakage, and sets an upper limit on VSWR should a port become short- or open-circuited. For a more detailed discussion of the Wilkinson divider/combiner (and other combiner circuits), see Ref. [1].

Examining the Magic Tee Hybrid

The magic tee replaces the transmission line sections of the Wilkinson divider with inductive windings on a ferrite core [2, 3]. Although the signal path diagrams appear similar, the method of operation is quite different.

First, we look at Figure 3, which is the tee configuration with additional detail on currents, voltages and impedances. At DC or low frequencies, we can easily see that the input voltage Vin will appear at each output. When the circuit is ideally balanced, the input current Iin will be equally divided between the two output ports, each having a current of Iin/2.

Ohm's Law then shows us that the impedance at the input is V_{in}/I_{in} and the impedance of each output is $V_{in}/(I_{in}/2)$. Without the impedance transformation seen in the Wilkinson divider, the outputs have an impedance 2× the input impedance. In practice, this impedance difference will require further transformation if the designer wants the same impedance at all ports.

In the power divider case, it is easy to see the relationships between input and output. The function of the balancing resistor R_b is less obvious, especially since it has no voltage drop or current if the output ports are terminated in the ideal impedance $2Z_{in}$ and has no effect.

In the fully balanced case, the longitudinal (common mode) currents in the magnetic material are equal and opposite, resulting in no net magnetic flux and its attendant loss. This makes the magic tee a near-ideal power divider when properly terminated.

If the port terminations deviate from $2Z_{in}$, R_b has the function of absorbing the excess power due to imbalance, limiting the difference in the two branch's currents, which then reduces loss in the ferrite material.

R_b should match the total impedance from Port 2 to Port 3, which is the series combination of each port's impedance. Thus, the correct resistance value is $R_b = 2\,Z_{out} = 4\,Z_{in}$. The photo of Figure 4 shows an implementation of several power dividers in an antenna switching unit. Each input has switchable R_b values to provide the correct value for two common input impedances.

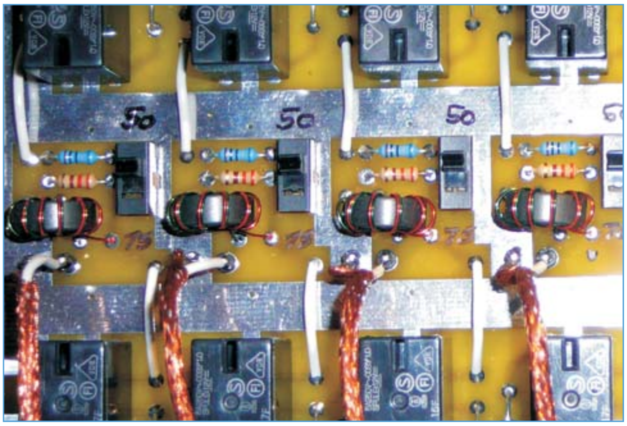

FIGURE 4

Photo of several magic tee hybrid power dividers in an HF antenna multicoupler/switching unit constructed by the author.

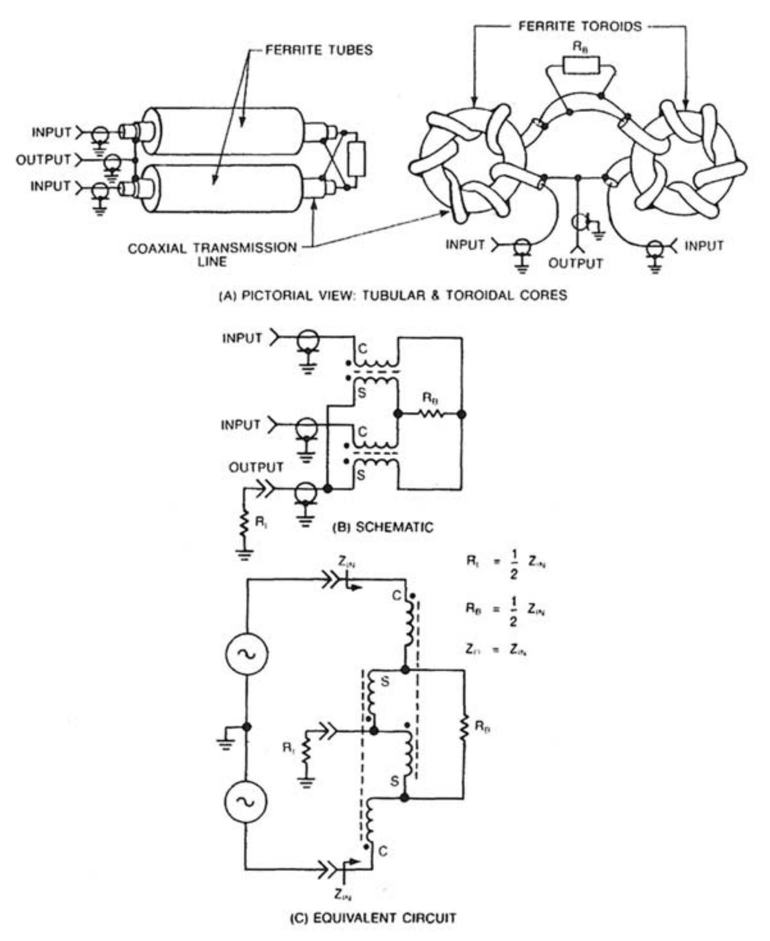

FIGURE 5

The two winding version ("Type 2") of the zero-degree hybrid. This design is intended for combining power amplifier modules into a high power amplifier system. (From Ref. [5])

An Alternate Topology

Figure 5 shows a two-core/four-winding version of the zero-degree hybrid. This implementation is sometimes called *Type 2*, with the magic tee referred to as *Type 1*. In the Type 2 hybrid, R_b is equal to the load impedance.

In practice, Type 2 achieves greater isolation than Type 1 [2, 5], since it has a "cross-coupled" topology that has multiple cancellation properties. Type 2 has poorer VSWR performance than Type 1, probably due to its greater complexity, which creates higher levels of parasitic inductance and capacitance. The designer's choice should consider these behaviors, along with the physical layout dictated by the inductor windings and connections to R_b.

Magnetic Materials

The magic tee hybrid relies on magnetic flux coupling to provide cancellation of longitudinal currents and achieve port-to-port isolation. The most common uses for these circuits are in HF/VHF power amplifier combiners, and in CATV power dividers.

At HF and at high power, ferrite materials with large cross-section and high μ_0 values will require the fewest turns (perhaps just one turn) and the shortest length of transmission line. The short delay will provide the smallest phase error, which helps reduce system losses. Various materials are available for operation from very low frequencies through the VHF range.

At the VHF/UHF range of CATV, iron powder cores with relatively low μ_0 will provide the necessary performance. The short wavelength makes it important to keep line lengths short, as well. Fortunately, receive-only power dividers operate a very low power levels and small-size cores can be used to help reduce overall size.

In all cases, the frequency of operation will dictate the necessary combination of core size, magnetic properties, and circuit layout and construction methods. With the right choices, these hybrid divider/combiners are valuable circuits for many RF applications in power amplifiers, antenna systems, receivers and test fixtures.

References

1. A. Grebennikov, *RF and Microwave Power Amplifier Design*, McGraw-Hill 2005, Ch. 5, "Power Combiners, Impedance Transformers and Directional Couplers."

2. J. Sevick, *Transmission Line Transformers*, 4th ed., Noble Publishing 2001, Ch. 17, "Notes on Power Combiners and Mixer Transformers."

3. N. Dye and H. Granberg, *Radio Frequency Transistors*, Butterworth-Heinemann 1993, Ch. 11, "Power Splitting and Combining."

4. J. L. B Walker, D. P. Myer, F. H. Raab and C. Trask, editors, *Classic Works in RF Engineering*, Artech House 2006, Ch. 2, "Magnetic Materials," and Ch. 5, "Hybrid Power Combiners and Splitters."

5. R. Blocksome, "Practical Wideband RF Power Transformers, Combiners, and Splitters," *Proceedings of RF Technology Expo '86*, pp. 207-227. (Also reprinted in Ref. [4].)