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Classic Designs for Lumped Element and Transmission Line 90-Degree Couplers

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This tutorial reviews the most familiar options for power division and combining with a 90-degree phase difference

Couplers (or power divider/combiners) with outputs that differ in phase by 90 degrees are an important part of RF/microwave design. This tutorial provides an overview of various types of 90-degree combiners, using both lumped element and transmission line structures. Our intention is to introduce the subject to engineers who may be unfamiliar with these couplers, and perhaps offer some reminders to experienced engineers who only occasionally use them in their designs.

Introduction

90-degree, or quadrature, couplers are used in applications such as power amplifiers, antenna feed systems, phase shifters, modulators/demodulators, image-reject mixers, measurement systems, and many others. Using the mathematics of sine/cosine trigonometric relationships, these circuits can provide isolation, reduce harmonic content, and improve linearity (reduce distortion). An added value of some couplers is the simplification of system design by simultaneously providing impedance transformation. Also, because there are numerous coupler topologies, designers have a wide range of choices for electrical performance, construction method, and physical size.

Note that coupler descriptions are made with the following convention: the common port will be referred to as the input, and each of the two 90-degree outputs will be referred to as an output or load. In other words, they will be described as power dividers. This is for convenience only, since the couplers are equally valid as 90-degree power combiners, where the flow of power is in the opposite direction.

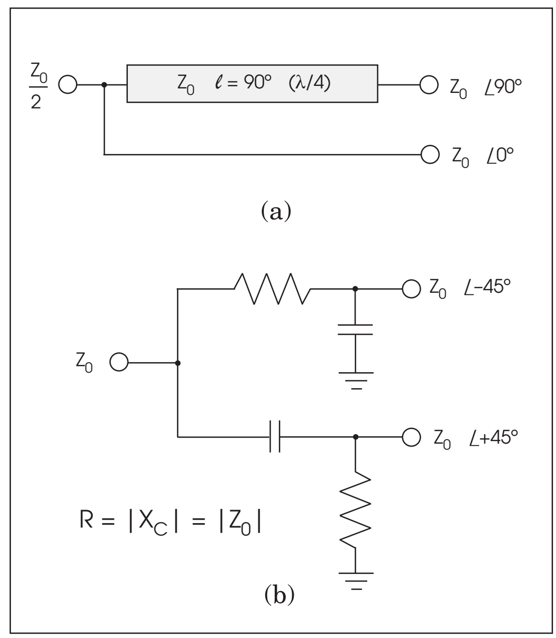

Figure 1 · Simple 90-degree power dividers can be made with (a) a delay line, (b) R-C equivalents.

Delay Lines

Transmission lines with an electrical length of 90 degrees at the operating frequency can provide the desired phase shift in some applications. R-C (or R-L) equivalent circuits can be used, as well [1] but they will have additional loss due to the resistive elements. Figure 1 shows these simple configurations.

These methods of obtaining the desired phase relationship have two significant disad-

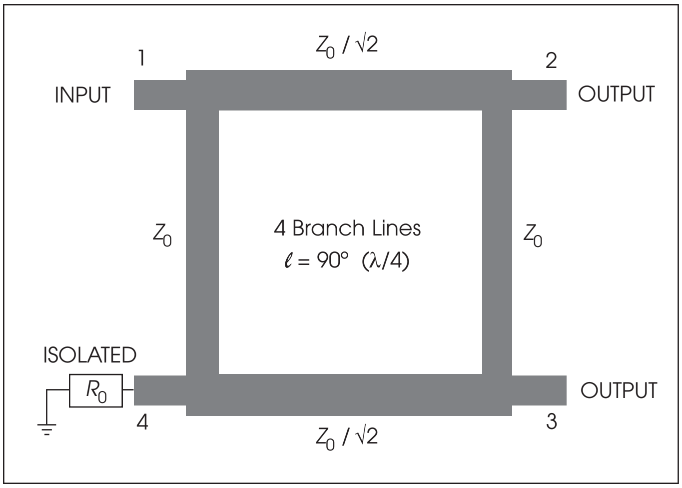

Figure 2 · The two-branch quadrature hybrid. The transmission lines can any type: coaxial, microstrip (shown here) or stripline. Ports are all Z_0.

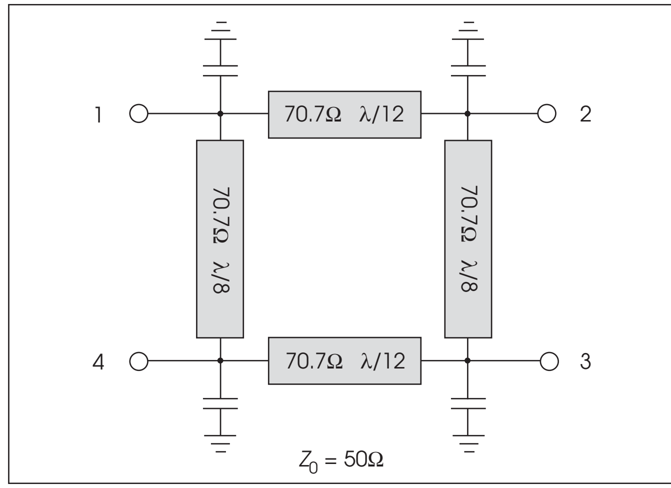

Figure 3 · A reduced-size coupler, using short line sections and shunt capacitors that are equivalent to the λ/4 lines of the branch line hybrid.

vantages. First, they require that both loads be essentially identical, and remain so over the frequency of operation. Second, there is no isolation between the ports. One of the few practical applications where these well-controlled characteristics exist is a quadrature power divider at the output of a fixed-frequency local oscillator, with the two outputs fed to buffer amplifiers with constant input impedances.

Two-Branch Quadrature Hybrid

The most common transmission line structure for these applications is the two-branch hybrid [2] shown in Figure 2. In a 50-ohm system, the transverse (vertically drawn) transmission lines are 50 ohms and the longitudinal (horizontal) lines are 35.4 ohms. All ports are 50 ohms, so the load is also 50 ohms. At the design frequency, when all ports are matched, power is delivered to ports 2 and 3 with a 90 degree phase shift between the ports. No power is delivered to the load.

Amplitude and phase accuracy deteriorate away from the design frequency, and the imbalance causes power to be delivered to the load. The usable bandwidth depends on the degree of precision required for the user's application. In many applications, this type of coupler is considered adequate for ±20 percent or more frequency deviation. Cascaded sections can be used to obtain wider bandwidths up to an octave or more.

By varying the characteristic impedances of the line sections, this coupler can be used to transform impedance, maintaining the desired 90-degree phase difference. This is useful, for example, when driving or combining outputs of devices in a balanced amplifier.

Figure 3 shows a reduced size version of the branch line coupler. The line sections are replaced with equivalent combinations of shortened lines and shunt capacitors. Although the occupied area is just 20 percent of the full-size coupler, bandwidth is only slightly reduced. The transmission line lengths shown are just one possible solution, chosen for line sections with the same impedance, equal to $Z_0/\sqrt{2}$. The capacitor values are the sums of the capacitances required for equivalence of each branch line

Branch line couplers may be constructed using any transmission line type—microstrip, stripline or coaxial cable. The method is chosen to suit the frequency of operation and the preferences of the user.

Coupled-Line Dividers

The coupled line divider of Figure 4 is another common means of obtaining quadrature outputs. As shown in the figure, the topology may be parallel lines or may include a crossover to place both outputs on the same side of the coupler, which will be more convenient for most applications.

With λ/4 line sections, the outputs of the coupled ports 3 and 4 are as follows [2, 3]:

$$S_{13} = -j\sqrt{1 - K^2}$$

$$S_{14} = K$$

where K is the coupling coefficient. Equal voltage division is obtained when $K = 1/\sqrt{2}$. With the requirement of strong coupling, these couplers may be implemented as cascades of two couplers with 3 dB coupling coefficient, which are less critical in their fabrication.

Another means of obtaining the desired K is the Lange coupler, which replaces the individual lines of the crossover version with a multiple interdigital structure. The Lange coupler is popular because it reliably provides the proper coupling, but additional crossover connections

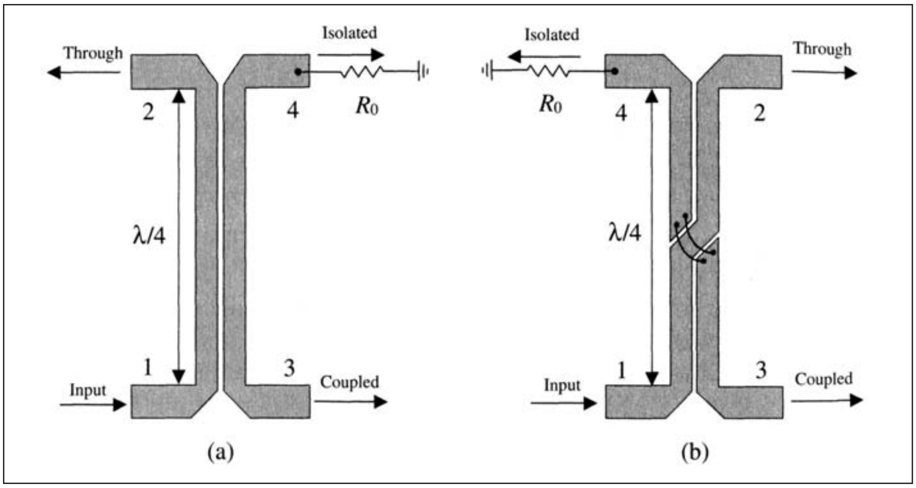

Figure 4 · The basic coupled line structure (a) and a crossover configuration (b) that locates both coupled ports on the same side (2).

result in a more complex and costly manufacturing process.

The coupled-line divider has lumped-element equivalents, as well. Figure 5 shows two such implementations. Fig. 5(a) replaces the transmission lines with a lowpass L-C network. These "lines" are uncoupled, so the coupling is obtained using two transformers. The transformers can also provide an impedance transformation for the selection of practical component values in the lowpass line sections. The author of Ref. [3] determined that a three-section lumped-element lowpass network provided a bandwidth equal to λ/4 coupled lines.

A simpler lumped element equivalent to the coupled-line divider is shown in Figure 5(b). Here, the coupling is provided in the inductors, which are wound in interlaced (bifilar) manner, using a ferrite or iron powder core to increase the magnetic flux and achieve mutual coupling approaching unity.

Port 1 or 2 may be the input, with the other port terminated in the characteristic impedance. Ports 3 and 4 are the quadrature outputs. The value of L is selected for 50 ohms reactance at the center frequency, while the capacitors have 100 ohms reactance. This network may also be shown with each capacitor identified as "$C/2$" where the value of C has the same 50 ohms reactance magnitude as the inductor [4].

This simple circuit has a practical bandwidth up to 50 percent of the center frequency, depending on the necessary accuracy. A cascade of two sections can provide an octave bandwidth. When cascading sections, isolating transmission line sections are required between the networks, which can also be implemented as lumped-element equivalents.

Summary

These classic 90-degree, or quadrature, couplers are key elements in many RF and microwave systems. For additional information, readers should note that the literature includes a large number of references on this subject in the literature. With the exception of [3], the ones listed here are recent works that have concise summaries that are useful as introductory material. These references, in turn, include additional references. Reference [4] includes selected reprints of seminal works on this and other topics.

References

1. W. Hayward, R. Campbell, R. Larkin, *Experimental Methods in RF Design*, American Radio Relay League, 2006, Chapter 9.

2. A. Grebennikov, *RF and Microwave Power Amplifier Design*, McGraw-Hill, 2005, Chapter 5.

3. R. De Lillo, "Lumped-Element Hybrids for Wide-Band Antenna Feed Networks," *Topics in Engineering*, AIL Systems, Inc., Vol. IV, 1993.

4. J. Walker, D. Myer, F. Raab, C. Trask, eds., *Classic Works in RF Engineering*, Artech House, 2006, Chapter 6.

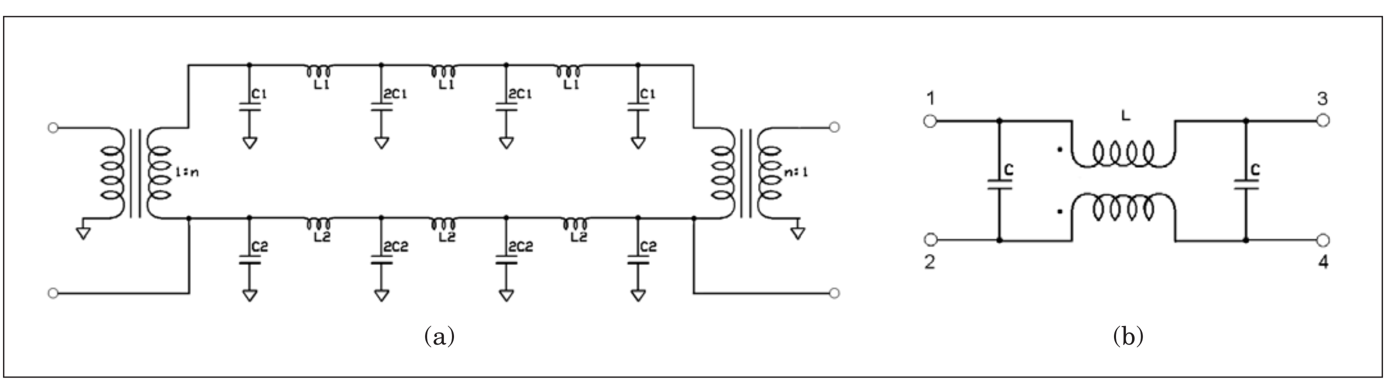

Figure 5 · These L-C couplers are derived from the coupled line divider: (a) uses transformer-coupled lowpass L-C sections, while (b) uses tightly-coupled inductances ($M \approx 1$) to provide the coupling.