

Transmission Line and Lumped Element Quadrature Couplers

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This month's tutorial article reviews the basic design and operation of power divider/combiners with ports that have a 90-degree phase difference

Quadrature couplers are used for power division and combining in circuits where the 90° phase shift between the two coupled ports will result in a desirable performance

characteristic. Common uses of quadrature couplers include:

Antenna feed systems—The combination of power division/combining and 90° phase shift can simplify the feed network of phased array antenna systems, compared to alternative networks using delay lines, other types of combiners and impedance matching networks. It is especially useful for feeding circularly polarized arrays.

Test and measurement systems—The phase shift performance may be sufficiently accurate for phase comparisons over a substantial fraction of an octave. A less critical use is to resolve phase ambiguity in test circuits. A number of measurement techniques have a discontinuity at 180°—as this value is approached, a 90° phase “rotation” moves the system away from that point.

Image-reject mixers—Two signal paths, using two mixers with quadrature LO signals and quadrature combining will mathematically cancel either the sum or difference term of the output. In practice, the unwanted mixing product can be reduced by 30 to 50 dB, depending on the operating frequency, bandwidth and level of precision.

Power amplifier combiners—Combining power amplifier modules in quadrature suppresses the third harmonic output, as well as some odd-order intermodulation products. If

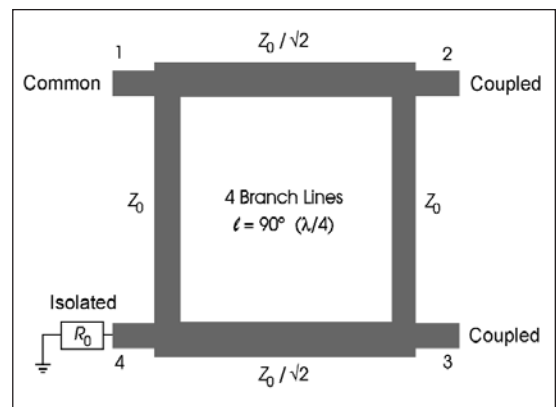


Figure 1 . The branch line quadrature hybrid, implemented using $\lambda/4$ transmission line sections.

each module has active devices in push-pull (180° combined), both even- and odd-order harmonics can be reduced, which simplifies output filtering.

In an earlier tutorial [1], I introduced a range of 90° coupler types without much analysis. In this article, we focus on the two main coupler types—the branch-line and coupled-line hybrids—in both their transmission line and lumped element implementations.

The term “hybrid” comes from the telephone wireline tradition, and refers to the presence of a port where there is a complete cancellation of the signal when the circuit is perfectly balanced—with equal amplitudes and accurate phases at all ports.

The Branch-Line Hybrid Coupler

Figure 1 shows the branch line quadrature hybrid, composed of four $\lambda/4$ transmission lines. Two lines have a characteristic

QUADRATURE COUPLERS

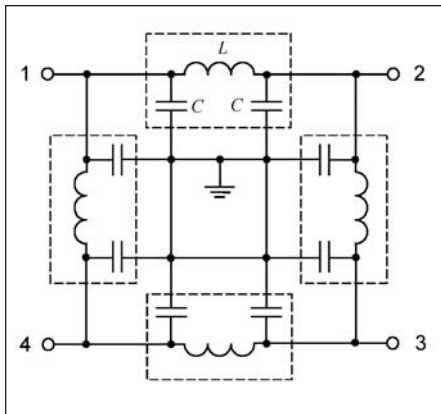


Figure 2 · Replacement of transmission lines with lumped element equivalent lowpass circuits.

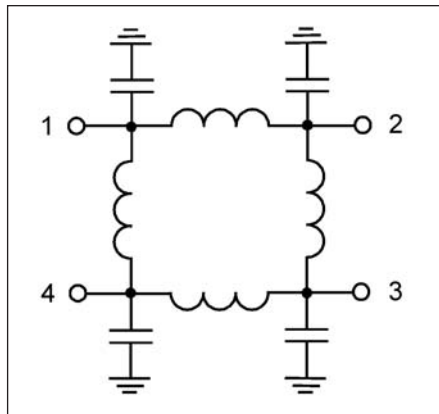


Figure 3 · The circuit of Figure 2, simplified by combining capacitors at branch junctions.

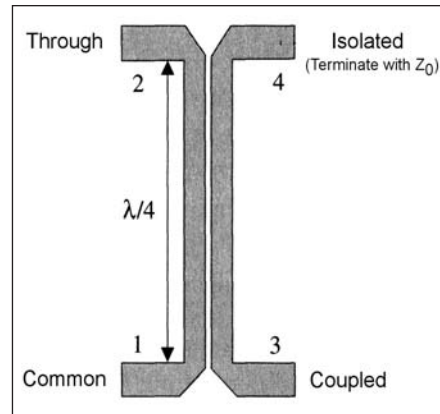


Figure 4 · The coupled-line hybrid provides quadrature coupling in a relatively compact physical size.

impedance of Z_0 , and two have an impedance of $Z_0/\sqrt{2}$. For a 50-ohm system, these lines will be 50 ohms and 70.7 ohms. The transmission lines may be coaxial, stripline or microstrip; whichever is a good fit for the frequency range and construction method.

This coupler has four ports: a common port, an isolated port, and two coupled ports with a 90-degree phase difference. When all ports are terminated with Z_0 , the isolated port load will dissipate no power, and the coupled ports will have identical power levels. The coupler structure is bilateral and may be used equally well as a power divider or power combiner.

The signal path through the coupler is straightforward. A signal applied to the common port has two paths to the isolated port, of $\lambda/4$ and $3\lambda/4$, with the $\lambda/2$ delay difference (180 degree phase difference) effectively cancelling one another.

The useful bandwidth of the branch line hybrid depends on the degree of amplitude and phase accuracy required by the application. Generally, it is considered to have a bandwidth of 10 to 20 percent, although the bandwidth can be readily extended through the use of cascaded coupler sections. A two-section coupler has a bandwidth of approximately half-octave.

Lumped Element Implementation

The branch line hybrid can be implemented using lumped element circuits that are equivalent to the $\lambda/4$ transmission line sections. Figure 2 shows this implementation with the line sections replaced by equivalent lowpass π -networks. This circuit is further simplified in Figure 3 by combining the two shunt capacitors at the network junctions into a single component.

The lumped-element equivalents of the transmission line sections can take the form of lowpass or highpass networks, depending on the designer's preference. The passband characteristics of the network can be useful in reducing filtering requirements elsewhere in the system.

The lumped element design has a narrower bandwidth than the transmission line coupler. This is often an acceptable tradeoff, especially at frequencies where the physical length of the transmission line segments is problematic. This is typically considered an issue at lower frequencies, but it also applies to very small circuits such as MMICs.

The Coupled-Line Hybrid

The coupled line hybrid shown in Figure 4 is another well-known design. When the mutual coupling between the parallel lines approach-

es unity—as is the case when they are $\lambda/4$ in length—the through and coupled ports have equal 3 dB power division and a 90 degree phase difference. The coupled line hybrid has the primary advantage of compact size, since the line sections must be adjacent to one another for near-perfect coupling.

[Note: This circuit is a directional coupler. When coupling is less than unity due to increased line spacing, line impedance differences, and/or line lengths less than $\lambda/4$, the coupled port will receive less of the incident signal. Such directional couplers are normally specified by the magnitude difference between the coupled and through ports, e.g., a “10 dB coupler” or “20 dB coupler.”]

In microstrip circuits, the resulting edge-coupled lines may not achieve sufficient coupling. A more complex arrangement, the Lange Coupler, with multiple interlaced “fingers” as the line sections is sometimes used. Stripline techniques may also be used; with the lines on adjacent layers, their width (not edges) provides the necessary coupling.

Lumped Element Implementation

Like the branch line hybrid, the coupled line hybrid may also be implemented in lumped element form. The equivalent circuit is shown

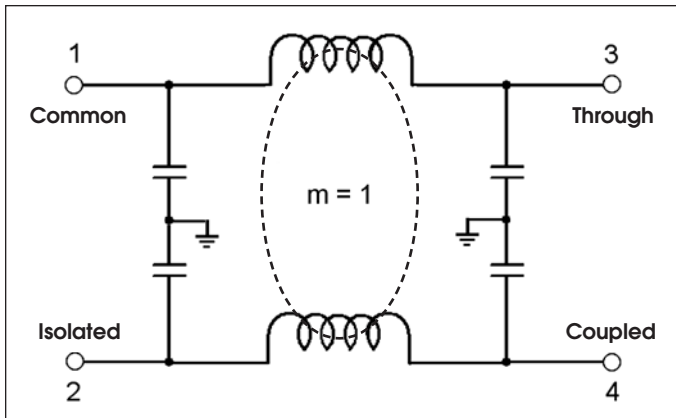


Figure 5 · Lumped element equivalent circuit, replacing transmission line sections with L-C sections. The primary difficulty in implementation is the need for two separate inductors with mutual coupling of unity.

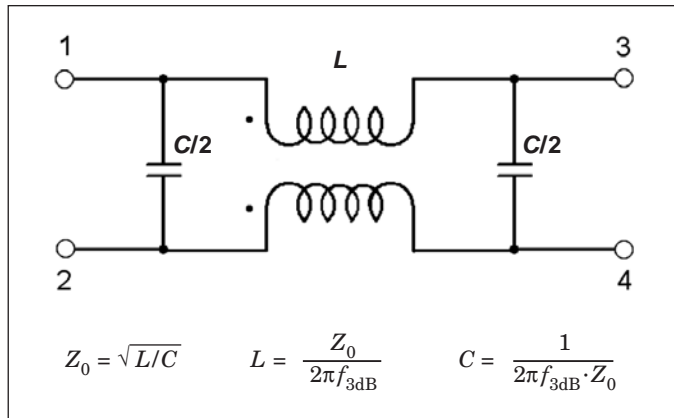


Figure 6 · This is the most common implementation of a lumped element coupled-line hybrid, with both inductors wound on a single magnetic core and end capacitors combined into single components.

in Figure 5. In this simplified form, it is not realizable, since the two branches must be coupled with near-unity mutual coupling.

The typical implementation is shown in Figure 6, where the two inductors are implemented as parallel or twisted-pair windings on a magnetic core. The magnetic core is a reliable method for achieving maximum magnetic flux required for near-unity mutual coupling. However, various parallel-wire inductor windings with air dielectric or a non-magnetic supporting core may be acceptable, usually resulting in narrower bandwidth. The end capacitors are nearly always combined into single components, as was done with the branch line hybrid.

In the final design of Figure 6, the values for L and C are derived from a classic equivalent circuit for a 90-degree transmission line section. This may be more familiar to some readers as a π -network, often used for impedance matching. In this case, there is no impedance transformation, but the network has the same 90-degree phase shift as a $\lambda/4$ transmission line. Other readers may best understand this equivalent circuit as being derived from a lowpass filter, which is also a valid approach.

The lumped element version of

this hybrid achieves amplitude balance of approximately ± 0.5 dB over a bandwidth of $f_0 \pm 10\%$. Amplitude dominates the total error; the relative magnitude of the phase error is much smaller.

Also note that the actual values of the end capacitors are $C/2$, since these components are the series combination of two capacitors (see Fig. 5), each having a value of C .

Using the design equations included in Fig. 6, a particular hybrid can be developed. For example, with a design frequency (f_{3dB} , commonly given as f_0) of 100 MHz and Z_0 of 50 ohms:

$$L = 50 / (2\pi \cdot 10^8) = 79.6 \text{ nH}$$

$$C = 1 / (2\pi \cdot 10^8) \cdot 50 = 31.8 \text{ pF}$$

$$C/2 = 15.9 \text{ pF}$$

The 79.6 nH inductor can be realized using a twisted pair of small-diameter wires, wound on a low permeability iron powder core, such as eight turns on a T25-12 core (0.25 inch dia., $\mu = 4$).

Scaling the hybrid to a much lower frequency of 10 MHz, results in values of:

$$L = 796 \text{ nH}$$

$$C/2 = 159 \text{ pF}$$

These are very practical values for a low frequency circuit. The inductor can be achieved using a twisted pair or parallel bonded wires, with a winding of 14 turns on a T37-2 core (0.375 inch dia., $\mu = 10$).

Winding these inductors is a simple task in the lab. In production, smaller diameter wire and a smaller magnetic core allows the construction of extremely compact networks. With the capability for such small size, it is easy to appreciate the popularity of this lumped element hybrid.

References

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