180° LUMPED ELEMENT HYBRID

Samuel J. Parisi

The MITRE Corporation
Bedford, Massachusetts

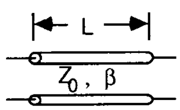
ABSTRACT

At frequencies below 18 GHz, distributed element hybrids consume too much valuable GaAs real estate to be cost-effective. An appreciable reduction in surface area without a degradation in electrical performance can be realized with the use of lumped element hybrids. This paper describes the design methodology employed in the development of a 180-degree lumped element hybrid. This technique is also applicable to other distributed devices such as the 90-degree branch line hybrid and the Wilkinson power divider.

INTRODUCTION

The conventional 180-degree transmission line hybrid or "rat-race" is depicted in figure 1. At frequencies below 18 GHz, this hybrid consumes too much valuable GaAs real estate to be cost-effective.. For later dimensional comparison purposes, a quarter wavelength on a 100 μm thick GaAs substrate at 8 GHz is 3240 μm. The electrical characteristics of this device, normalized to 1 Hz, are also shown in figure 1. Due to symmetry, the return losses of ports three and four are not shown. The same is true of the other return loss curves that will be displayed. An appreciable reduction in surface area can be realized with the use of a lumped element hybrid. This paper describes the design methodology employed in the development of a 180-degree lumped element hybrid.

The technique used was to derive equivalent "pi" and "tee" networks for the transmission line segments of the "rat-race." This task was accomplished by equating the ABCD matrix elements for the transmission line segments to the ABCD matrix elements for the lumped element networks at the design frequency. The matrix operations are outlined below:



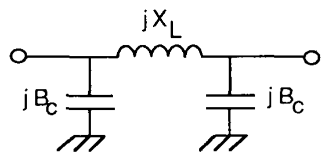
$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} \cos\beta L & jZ_0 \sin\beta L \\ jY_0 \sin\beta L & \cos\beta L \end{bmatrix}$$

Lossless transmission line (α = 0)

For $\beta L = 90°$,

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 0 & jZ_0 \\ jY_0 & 0 \end{bmatrix}$$

This transmission line segment can be modeled as a low-pass "pi" network as shown below where the shunt element admittance and series element impedance are given:



$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ jB_C & 1 \end{bmatrix} \begin{bmatrix} 1 & jX_L \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ jB_C & 1 \end{bmatrix} = \begin{bmatrix} 1 - X_L B_C & jX_L \\ jB_C(2 - X_L B_C) & 1 - X_L B_C \end{bmatrix}$$

A "pi" equivalent low-pass section is preferred to a "tee" since there are fewer inductors. Spiral inductors exhibit relatively high resistive losses.

Equating the matrix elements of the "pi" network to the matrix elements of the transmission line segment yields the following results:

$X_L B_C = 1$ and $X_L = Z_0$

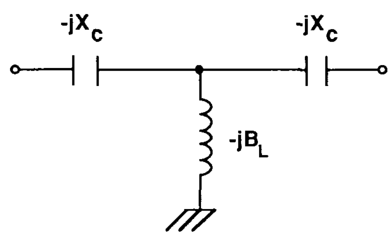
Therefore, $B_C = Y_0$.

For the 270-degree transmission line, we can substitute βL equalling 270 degrees and achieve the following ABCD matrix:

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 0 & -jZ_0 \\ -jY_0 & 0 \end{bmatrix}$$

A high-pass "tee" network allows easy matching of this ABCD matrix, and as before it has fewer inductors than a high pass "pi" network.

The high-pass "tee" and its ABCD matrix are show below again with shunt element admittance and series element impedance given.



$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & -jX_C \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -jB_L & 1 \end{bmatrix} \begin{bmatrix} 1 & -jX_C \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 1 - B_L X_C & -jX_C(2 - B_L X_C) \\ -jB_L & 1 - B_L X_C \end{bmatrix}$$

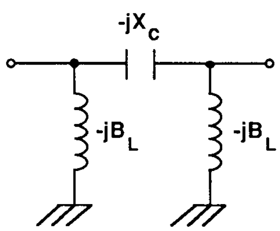
Equating the matrix elements of the "tee" network to the matrix elements of the transmission line segment yields the following results:

$$B_L X_C = 1 \text{ and } B_L = Y_0$$

Therefore, $X_C = Z_0$.

The final circuit configuration is shown schematically in figure 2 along with its electrical characteristics. The performance is normalized to 1 Hz.

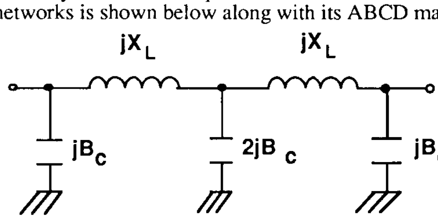
A simplified version of this circuit which employs fewer components can be realized by employing a high-pass "pi" network instead of a "tee" network for the 270-degree transmission line segment. This is shown below along with its ABCD matrix again with shunt admittance and series impedance:



$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 - B_L X_C & -jX_C \\ -jB_L(2 - B_L X_C) & 1 - B_L X_C \end{bmatrix}$$

The shunt inductors of the high-pass "pi" network are resonant with the shunt capacitors of the low-pass "pi" network at the design frequency and these components are removed which yields an attendant reduction in bandwidth. The circuit is shown schematically in figure 3 along with its electrical performance.

Broader bandwidth at the expense of slightly higher loss can be obtained by employing a cascade of two sections in each arm of the hybrid. The low-pass network which consists of two "pi" networks is shown below along with its ABCD matrix:

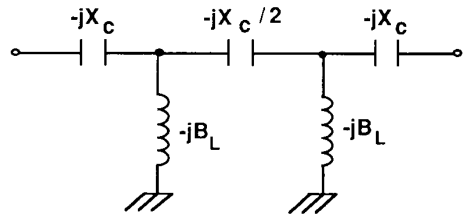


$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} =$$
$$\begin{bmatrix} 1 - 4X_L B_C + 2X_L^2 B_C^2 & 2jX_L(1 - X_L B_C) \\ 2jB_C(1 - X_L B_C)(2 - X_L B_C) & 1 - 4X_L B_C + 2X_L^2 B_C^2 \end{bmatrix}$$

Equating the matrix elements as before to the 90-degree transmission line ABCD matrix yields the following results:

$$X_L = \frac{Z_0}{\sqrt{2}} \text{ and } B_C = (\sqrt{2} - 1)Y_0$$

The high-pass network which consists of two "tee" networks is shown below along with its ABCD matrix:



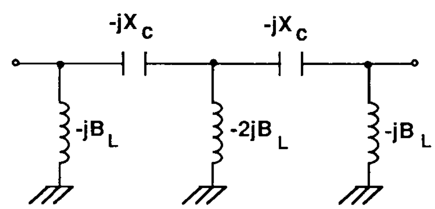
$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} =$$
$$\begin{bmatrix} 2B_L^2 X_C^2 - 4B_L X_C + 1 & -j2X_C(2 - B_L X_C)(1 - B_L X_C) \\ -2jB_L(1 - B_L X_C) & 2B_L^2 X_C^2 - 4B_L X_C + 1 \end{bmatrix}$$

Equating the matrix elements as before for the 270-degree line yields the following results:

$$B_L = \frac{Y_0}{\sqrt{2}} \text{ and } X_C = (\sqrt{2} - 1)Z_0$$

The total circuit schematic is displayed in figure 4 along with its electrical performance.

A simplified version of this circuit , i.e. fewer elements, with very little loss of performance can be realized by employing a high-pass section which is a cascade of two "pi" networks. This network is shown below along with its ABCD matrix:



$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} =$$
$$\begin{bmatrix} 1 - 4X_C B_L + 2X_C^2 B_L^2 & -2jX_C(1 - B_L X_C) \\ -2jB_L(2 - B_L X_C)(1 - B_L X_C) & 1 - 4X_C B_L + 2X_C^2 B_L^2 \end{bmatrix}$$

The capacitive reactance and the inductive susceptance are calculated to be:

$$X_C = \frac{Z_0}{\sqrt{2}} \text{ and } B_C = (\sqrt{2} - 1)Y_0$$

Here, as in the narrower bandwidth single section version, the shunt capacitors and the shunt inductors at ports two and four are resonant at the design frequency and are removed. The circuit schematic is shown in figure 5 along with its electrical performance.

The layout of an actual hybrid designed for a center frequency of 7.95 GHz is shown in figure 6. This circuit is the realization of the hybrid shown in figure 2. The circuit includes probe pads for device characterization. The dimensions of the hybrid alone are 850 μm by 700 μm which is a large savings in area over the transmission line version which could be 16 times larger on a side. Calculated performance of this device which includes the loss components of the spiral inductors, microstrip discontinuities and transmission lines is shown in figure 7.

CONCLUSION

A technique for the design of 180-degree lumped element hybrids has been described which yields electrical performance comparable to the transmission line version but with significantly smaller area. Broader bandwidth can be obtained by cascading two lumped element sections. This technique is also applicable to other distributed devices such as the 90-degree branch line hybrid and the Wilkinson power divider.

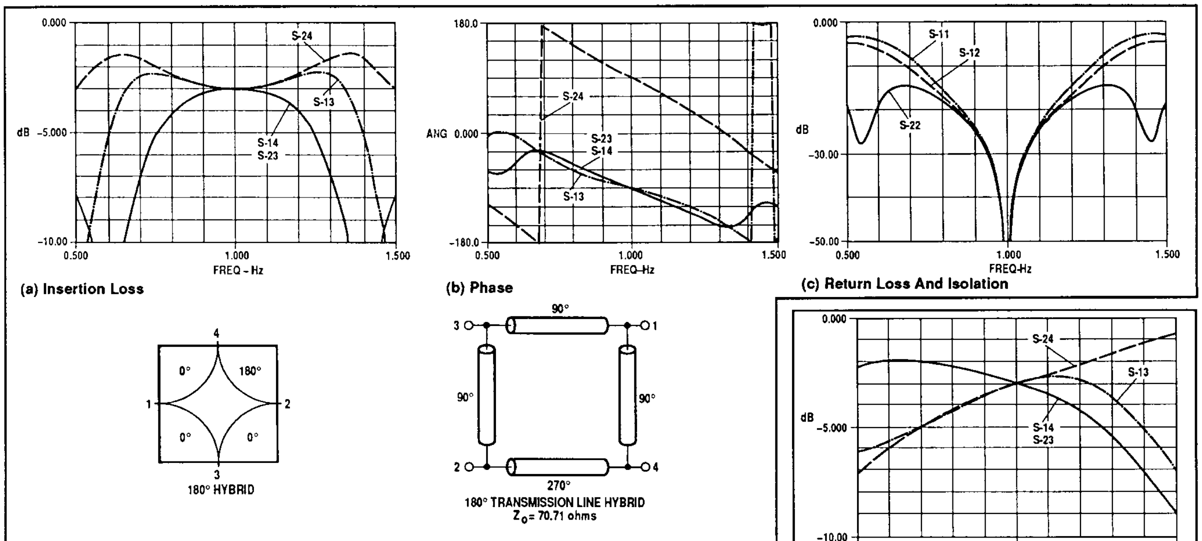


Figure 1. Transmission Line Hybrid

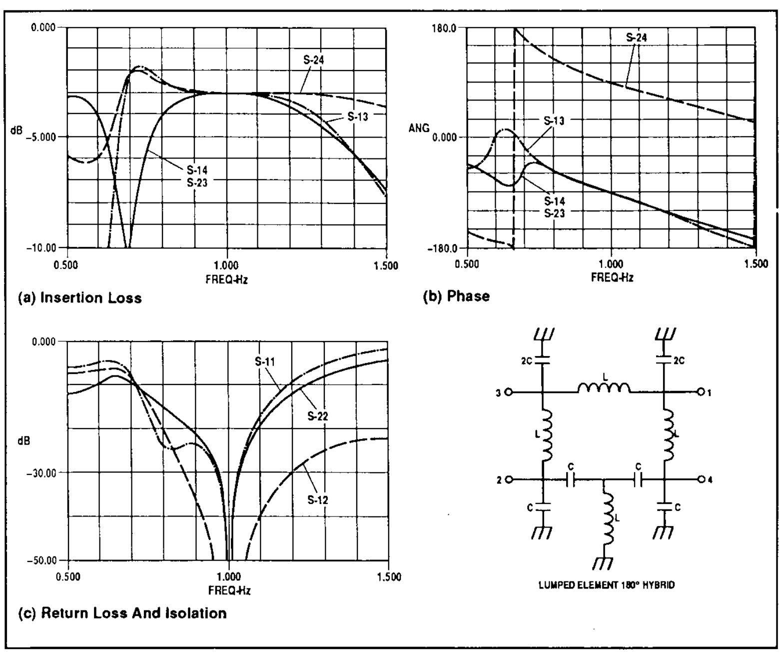


Figure 2. 180° Lumped Element Hybrid

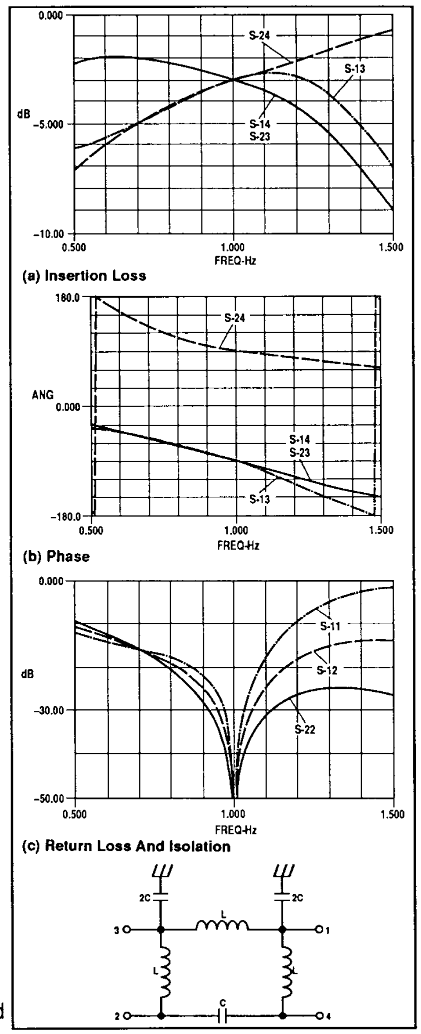
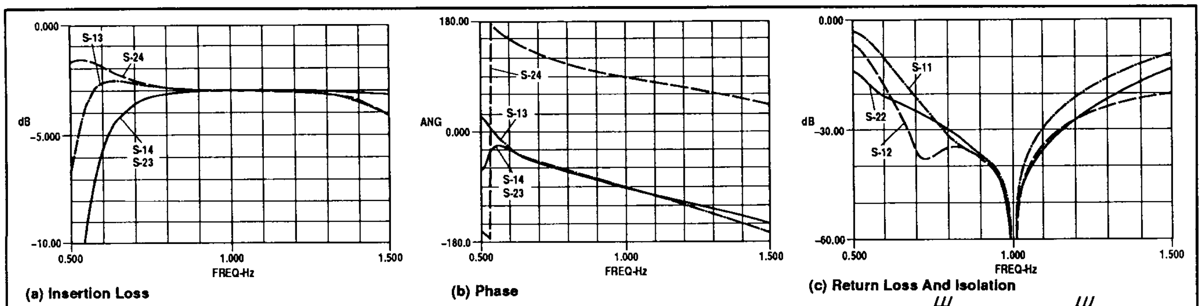


Figure 3. Narrow Band 180° Lumped Element Hybrid



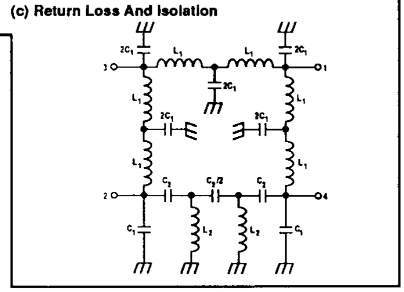


Figure 4. Broadband 180° Lumped Element Hybrid

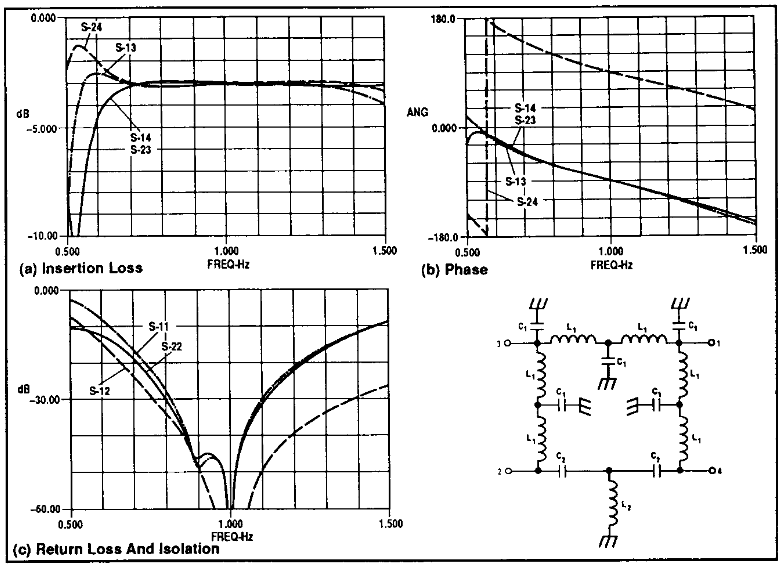


Figure 5. Simplified Version Of Broadband Hybrid

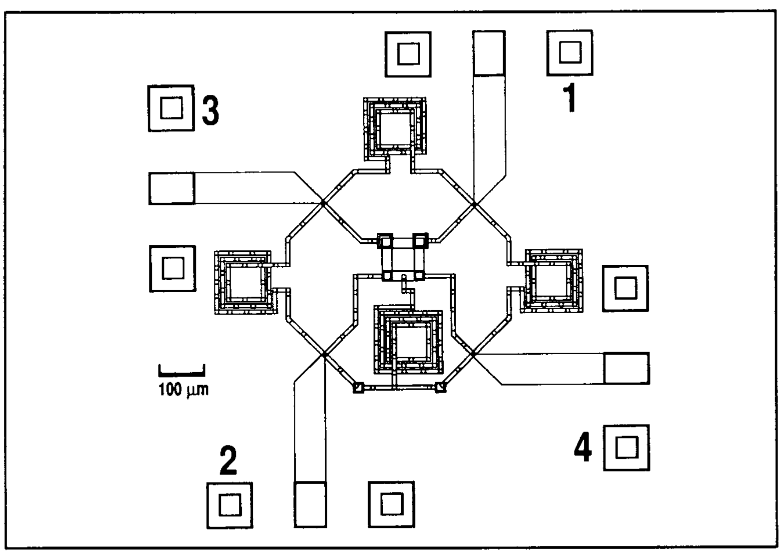


Figure 6. Physical Layout Of 180° Lumped Element Hybrid

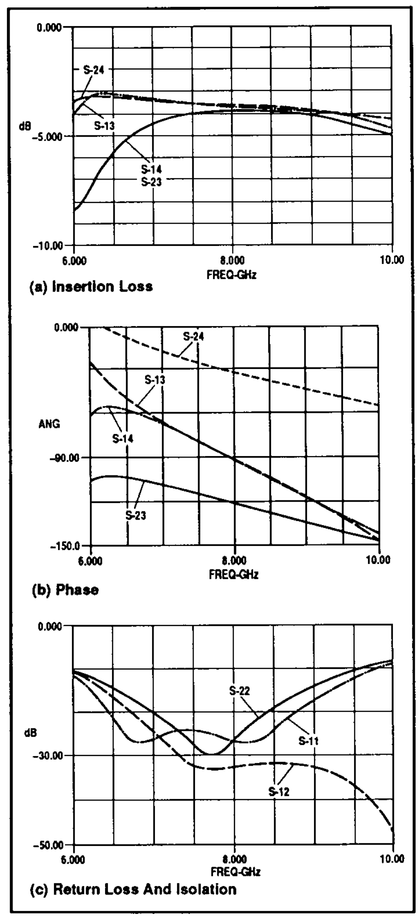


Figure 7. Predicted Performance Of Hybrid