A Spiral Microwave Directional Coupler for MIC Application

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Summary

A new spiral-shaped directional coupler for MIC is proposed. The feature is the compact size and the tight coupling with wide strip spacing. The analysis, design chart and test results are given.

Introduction

In general, the branch-line and backward wave type couplers have been used as a directional coupler in the microwave integrated circuits. The former is easily manufactured, but the frequency band of operation is narrow. The latter's band is wide, but the spacing of the parallel coupled lines is dependent on the degree of coupling. Therefore, tight coupler, for example, 3 dB hybrid, cannot be fabricated in the conventional method, because the spacing becomes below 2 μm. To avoide this difficulty, the interdigitated microstrip directional couplers have been proposed.[1,2,3] The coupler constructed from the coupled lines with tuning septums is also reported.[4] The couplers mentioned above, however, are the same size as or larger than the earlier.

In this report, a new microwave directional coupler with a spiral-shaped construction is proposed and named "spiral coupler". The spiral coupler is formed by bending the conventional backward wave coupler made up of parallel coupled lines. Therefore, the size of a coupler becomes smaller in a great degree than the conventional one. The more important feature is that the recoupled power, which is a portion of transmitted one, increases the degree of coupling on account of the multiconductor structure. The 1.5 turn coupler is analyzed in detail and the comparison of the theoretical data with experimental one is shown. In addition, the design chart of 2 turn coupler is described. The method of broadening the bandwidth of a spiral coupler is also shown.

Construction and Equivalent Circuit

In Fig.1, the construction of a spiral coupler (1.5 turn) is depicted. In the hatched area Ⓐ, a portion of the transmitted power to the output port is recoupled and tight coupling is obtained consequently. The total length of the coupler is a quarter of the guide wavelength ($\lambda_g/4$) at center frequency. A side of the coupler l is about $(\lambda_g/4)/6$ in 1.5 turn coupler, so, the size can be miniaturized. The spiral coupler in Fig.1 is equivalent to the 4-port circuit in Fig.2, which is composed of coupled two and four transmission lines.

Analysis

Scattering Matrix

The scattering matrix (S) of a coupler can be calculated from (1).

$$S = Z_l^{\frac{1}{2}} (Y_l - \tilde{Y})(Y_l + \tilde{Y})^{-1} Z_l^{-\frac{1}{2}} \tag{1}$$

where Y_l ($= Z_l^{-1}$) is the load admittance matrix, $Z_l^{\frac{1}{2}}$ is the square root matrix of Z_l and $\tilde{Y}$ is the admittance matrix of the equivalent circuit.

$\tilde{Y}$ of 1.5 turn coupler is obtained as

$$\tilde{Y} = y_3 + y_4 (A - y_1)^{-1} y_2 \tag{2}$$

As the matrix $Y = [Y_{ij}]$ of coupled four lines whose length $2l$ is partly symmetric, $y_1 \sim y_4$ are expressed in (3).

$$y_1 = \left[\begin{array}{cc|cc} Y_{22} & Y_{12} & Y_{17} & Y_{27} \\ Y_{12} & Y_{11} & Y_{18} & Y_{17} \\ \hline Y_{17} & Y_{18} & Y_{11} & Y_{12} \\ Y_{27} & Y_{17} & Y_{12} & Y_{22} \end{array}\right] = \begin{bmatrix} y_1^{11} & y_1^{12} \\ y_1^{21} & y_1^{22} \end{bmatrix}, \quad y_2 = \left[\begin{array}{cc|cc} Y_{13} & Y_{23} & Y_{26} & Y_{16} \\ Y_{14} & Y_{13} & Y_{16} & Y_{15} \\ \hline Y_{15} & Y_{16} & Y_{13} & Y_{14} \\ Y_{16} & Y_{26} & Y_{23} & Y_{13} \end{array}\right] \tag{3}$$

$$y_3 = \begin{bmatrix} y_1^{22} & y_1^{21} \\ y_1^{12} & y_1^{11} \end{bmatrix}, \quad y_4 = y_2'$$

where the prime denotes matrix transpose.
The matrix A is calculated from chain matrix (a, b, c) of coupled two lines as

$$A = \begin{bmatrix} -b^{-1}a & b^{-1} \\ -c + ab^{-1}a & -ab^{-1} \end{bmatrix} \tag{4}$$

where a, b, c are given in (5).

$$(\tilde{v}_1, \tilde{v}_2, \tilde{i}_1, \tilde{i}_2)' = \begin{bmatrix} a & b \\ c & a \end{bmatrix} (\tilde{v}_{1L}, \tilde{v}_{2L}, \tilde{i}_{1L}, \tilde{i}_{2L})' \tag{5}$$

About 2 turn coupler, $\tilde{Y}$ is similarly obtained.

Admittance Matrix of Coupled Four Lines

The admittance matrix parameters of the coupled four line eight-port circuit (Fig.2) are found in terms of the normal mode characteristic admittances of the four lines, the mode voltage eigen vectors and the propagation constants for the normal modes.

Capacitance Matrix

The admittance matrix in the previous section is derived by the capacitance matrix. In order to obtain the capacitance matrix of the coupled four lines, the capacitances for even and odd mode excitation must be known. The coupling section under analysis is shown in Fig.3, which is shielded by a rectangular outer conductor. We restrict the structure to be symmetric at x=0 for simplicity. We have made use of the spectral domain formulation[5] and applied the Galerkins' method in order to obtain the capacitances. Before generating reliable numerical results, we have tested several different basis functions. In addition, we have examined numerically that the capacitance matrix is hyperdominant. The same procedure gives the even and odd mode capacitances of the coupled two lines.

Design and Trial Production

Design Chart

When the spacing of strip conductors normalized with the substrate thickness (2S/h), the width (W/h) and the relative dielectric constant (ε_r) of the substrate are given, the guide wavelengths of modes are calculated, from which the total length of a coupler can be determined as a quarter of the averaged guide wavelength. Furthermore, the length must be adjusted to obtain maximum coupling at center frequency. In Fig.4, the charts for alumina substrate (ε_r=9.6) are shown. The quantity $\tilde{L}$ is the effective guide wavelength normalized with the free space one, λ_0.

Test Result

The spiral couplers of two types were produced on an alumina seramic substrate of 0.635 mm thickness. The dimensions are shown in Table 1.

	W(mm)	2S(mm)	L(mm)	f_0(MHz)	$C_0'^*$(dB)	Cmax(dB)
#1	0.395	0.040	48.51	750	5.88	3.45
#2	0.454	0.063	48.37	750	6.87	4.55

* Maximum coupling at center frequency when the coupler is used as a conventional backward wave type coupler.

Table 1. Design parameters of two couplers for trial construction (actual, not intended.)

The data (Fig.5) show that the return losses are more than 20 dB, 25 dB respectively and the directivities are more than 21 dB for both couplers over a octave band, which is from 500 MHz to 1 GHz. The frequency characteristics of coupling were in good agreement with the calculated ones within a maximum discrepancy 0.50 dB(#1) and 0.15 dB(#2) over the same band. The phase difference of coupled and transmitted wave was tested about #1 coupler which has 3 dB coupling. The result was that the deviatin of the phase difference from 90 degrees was ± 3 degrees over the above-mentioned band. Therefore, the phase relation was sufficient as a 90° hybrid.

Broadening the Bandwidth of a Spiral Coupler

The spiral coupler in Fig.1 is equivalent to 1-section transmission line directional coupler. When we adopt the configuration as in Fig.6, the frequency bandwidth of the coupler becomes broad, because it is equivalent to the directional coupler with 3 sections. With teflon glass substrate, we manufactured the coupler with the configuration in Fig.6. By making use of the circuit in Fig.1 with 6.5 dB coupling at 800 MHz, we obtained 3.5 dB maximum coupling about the new coupler as shown in Fig.7. The center frequency shifted from 800 MHz to 2.0 GHz. Therefore, this method is quite useful for broadening the bandwidth of a spiral coupler.

Conclusion

The method of analysis, design charts and test results of the spiral coupler are given.

We have extended the result in the reference (6) and applied the spectral domain method[5] for analysis. The design charts for necessary coupling were drawn with the spacing and width of strip conductors as the design parameters. The couplers for trial construction with 3~4 dB coupling presented the preferable results. In addition, we mentioned the method of broadening the bandwidth of a spiral coupler.

References

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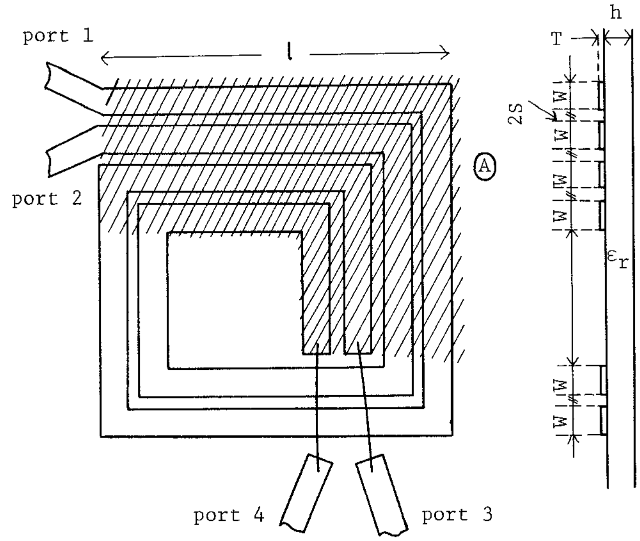

Fig.1. Construction of a spiral coupler (1.5 turn) (Total length is equal to $\lambda_g/4$)

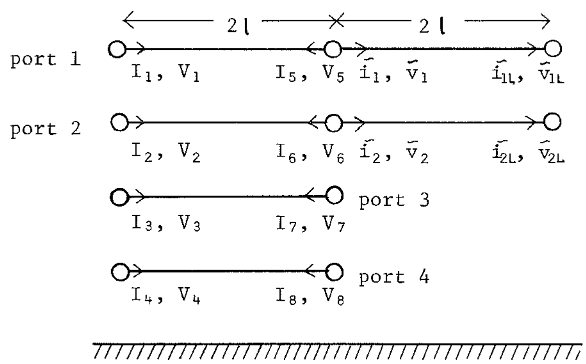

Fig.2. Equivalent circuit of a spiral coupler (1.5 turn)

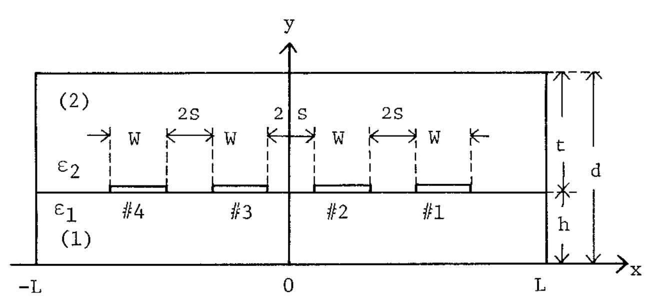

Fig.3. Model for calculation of the capacitance matrix of coupled four lines

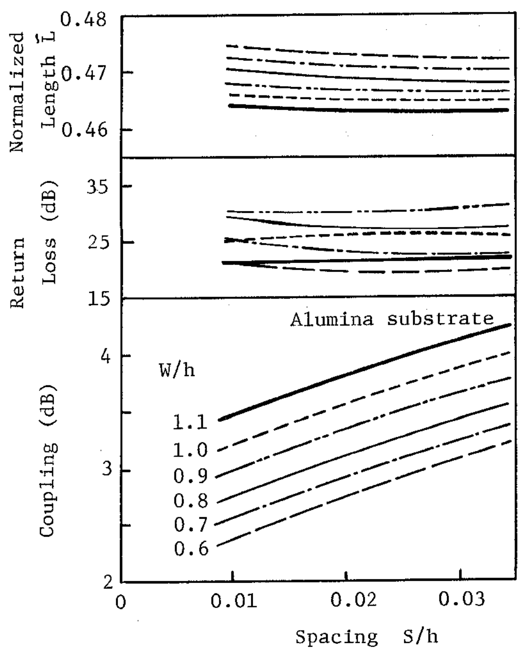

Fig.4 (a). Design chart of a spiral coupler (2 turn)

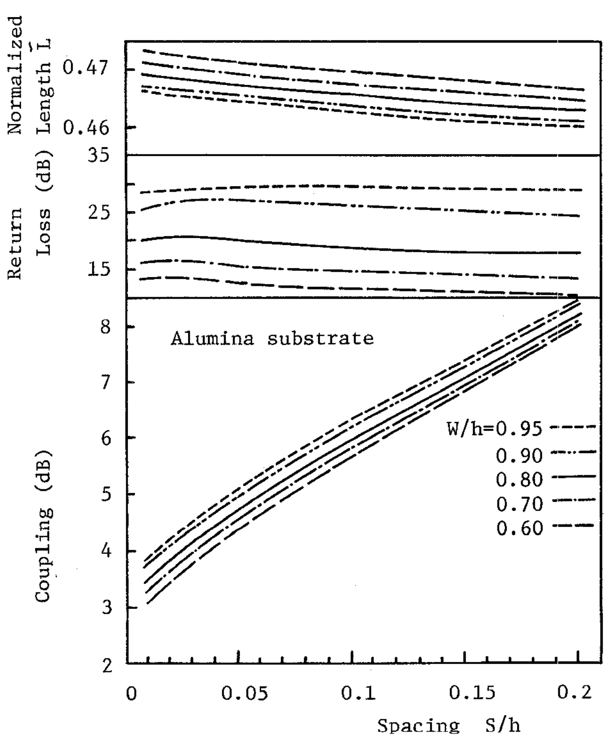

Fig.4 (b). Design chart of a spiral coupler (1.5 turn)

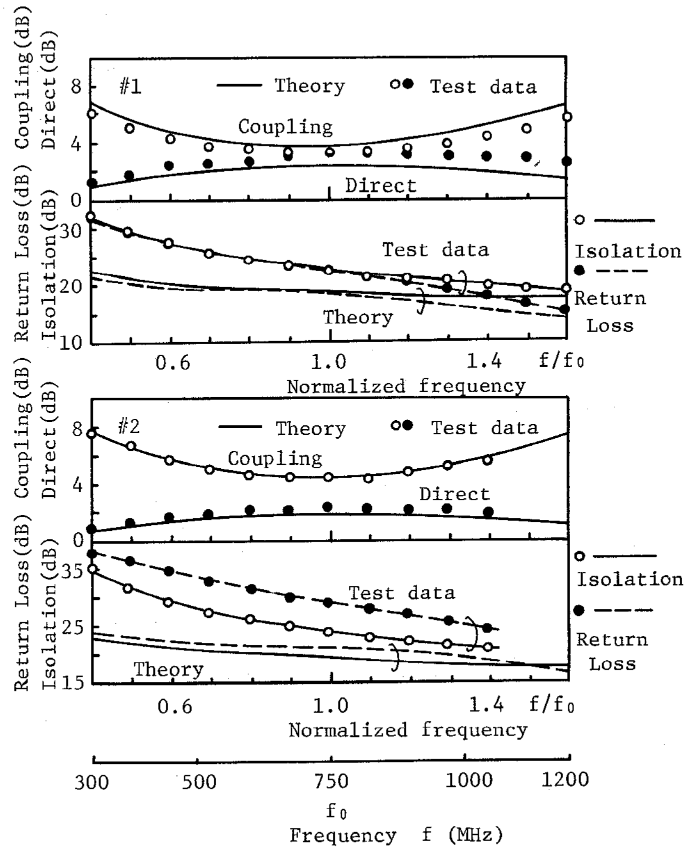

Fig.5. Test data (dots) of 1.5 turn spiral coupler

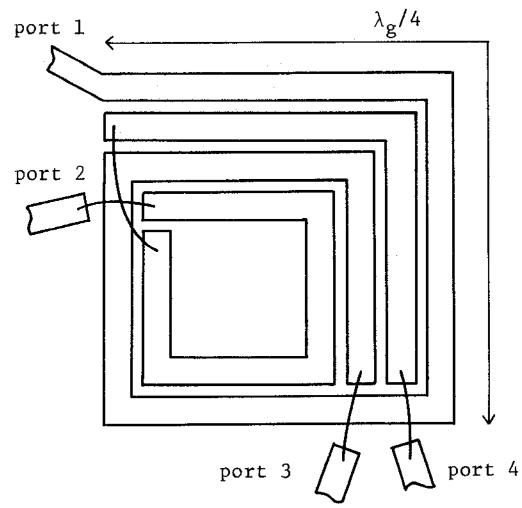

Fig.6. Modification of a spiral coupler in Fig.1 for wider band operation (Total length is equal to $3\lambda_g/4$)

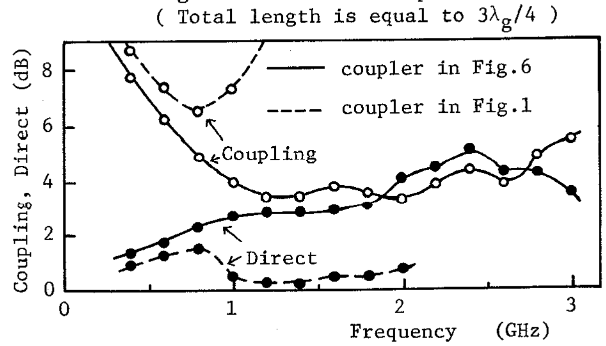

Fig.7. Test data of a spiral coupler in Fig.6