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WIGGLY PHASE SHIFTERS AND
DIRECTIONAL COUPLERS FOR
RADIO FREQUENCY HYBRID
MICROCIRCUIT APPLICATIONS

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Summary

Packaging microwave hybrid microcircuits having combined electrical functions presented challenges in meeting space requirements without excessive signal interaction between microwave networks. The dispersive characteristics of microwave hybrid microcircuits are aggravated by the proximity of conductive materials, which places stringent requirements on packaging space and geometry.

Directional couplers and phase shifters are two types of thin film networks which require large amounts of hybrid microcircuit real estate. Directional coupler characteristics are also sensitive to microwave energy propagation velocity dispersion (hereafter called dispersion) which is characteristic of hybrid microcircuit (microstrip) geometry.

A technique suggested by A. F. Podell¹ for reducing the effects of microstrip dispersion on directional couplers was investigated. This technique provides a means of slowing "odd" mode microwave energy propagation velocity to equal the "even" mode propagation velocity.

The means for slowing the odd mode propagation velocity is provided by a wiggly (sawtooth) conductor edge between adjacent conductors. This provides the slowing action because the odd mode energy has significant content in the air space above the substrate between the adjacent conductors and must travel the increased distance provided by the wiggly edge. The even mode energy is primarily contained within the substrate material between the conductor and ground plane on the opposite side of the substrate and travels the straight-line distance of the conductor.

A number of thin film networks of directional couplers and phase shifters were fabricated on alumina substrates having prescribed geometry variations. The microwave characteristics were measured and relationships between geometry and the characteristics were established. The microwave characteristics of the wiggly phase shifter and directional coupler are compared with microwave characteristics of the thin film networks produced by previous straight line methods.

A space savings of 15 to 20 percent has been achieved with the wiggly phase shifter and wiggly directional coupler. In addition, the performance of each device has been significantly improved. The VSWR bandwidth of the phase shifter has been doubled, and the directivity of the directional coupler has been increased by 20 dB.

Problem Definition

Dispersion

Microwave energy is propagated in electromagnetic fields either surrounding conductor paths or contained

within conducting enclosures. The energy within these fields travels at the speed of light divided by the square root of the product of the relative dielectric constant and relative permeability of the propagation medium.

When two or more dielectric materials are employed in a microwave circuit, some of the microwave energy will travel at a different velocity than the remaining energy, depending on the portions of the electromagnetic fields which are contained within the different dielectric mediums. As can easily be visualized, the larger the difference in relative dielectric constant or relative permeability of the different dielectric mediums, the larger will be the dispersion. The conductor size and its placement with respect to other conductors significantly affects the division of the electromagnetic fields between the different dielectric mediums.

Microwave HMCs at Bendix Kansas City are fabricated on alumina substrate material 0.69 ± 0.03 mm thick which has a relative dielectric constant of 9.6, with air being the second dielectric medium. The permeability of this system is very near that of free space; that is, the relative permeability is very near 1.0. The primary dispersive agent, therefore, is the relative dielectric constant of the alumina. Figure 1 is a qualitative sketch of the electric fields of this type of microwave system.

The odd and even mode fields of a two conductor (plus ground) system are also shown in Figure 1. These two modes exist down to dc where they reduce to TEM. The dispersion becomes more pronounced as frequency is increased. In spite of these effects, most HMC designs can be achieved by assuming TEM propagation with an appropriately chosen effective dielectric constant.

The effects of dispersion are more pronounced, however, as line spacing is reduced to fabricate directional

Figure 1. Electric Fields of Microstrip Shown in Cross Section

couplers and phase shifters. In couplers, circuit function is degraded by a significant loss of directivity; in phase shifters the low VSWR band width is reduced and displaced from the center frequency of operation. This deterioration in circuit operation makes compensation for dispersion desirable.

Effective Dielectric Constant

The effective dielectric constant is dependent upon the ratio of the microwave fields contained in the substrate to those contained in the air. The more the microwave fields are concentrated in the substrate material the closer the effective dielectric constant will approach that of the substrate material. The geometry of the TFN has a strong influence on the degree of microwave field concentration within the substrate material. For example, wide conductors will have higher effective dielectric constants than will narrow conductors, and the closer conductors are spaced the lower will be the effective dielectric constant. The problem of determining the appropriate dielectric constant is difficult except for simple TFN designs.

Even and Odd Mode Characteristic Impedance

The characteristic impedance of a lossless distributed transmission line is the square root of the ratio of the inductance per unit length to the capacitance per unit length. In the microstrip environment, the capacitance per unit length is radically different for the two modes of propagation. It is convenient, therefore, to define an odd mode characteristic impedance (Z_{0o}) and an even mode characteristic impedance (Z_{0e}) relative to the two modes of propagation.

Slowing the Odd Mode Propagation Velocity

The odd mode velocity can be slowed by providing extra distance for the odd mode wave to travel. This can be accomplished by wiggling the edges of adjacent conductors because a significant portion of the odd mode field is contained between the conductors. The even mode fields are not appreciably affected if only one edge of the conductor is wiggled. Therefore, microwave propagation velocities can be matched by carefully choosing wiggle lengths and conductor spacings.

Empirical Approach

Because of the limited data available on directional couplers and wiggly phase shifters, several devices were fabricated to access the relationship between device function and TFN geometry. The devices were fabricated on 0.69 mm thick alumina substrates having approximately 6 μm of metalization. The frequencies of interest were VHF to C-band (100 MHz to 4.0 GHz). Since the geometry for a phase shifter and a directional coupler are quite different, different experiments were designed for each type TFN.

Directional Couplers

Five variables require definition for the fabrication of directional couplers:

- Optimum wiggly geometry,
- Conductor spacing,
- Length of coupling section,
- Even and odd mode characteristic impedance, and
- Effective dielectric constant.

These variables are all interrelated and must be defined in terms of the following coupler performance criteria:

- Coupling loss versus frequency,
- Isolation (or directivity) versus frequency,
- Insertion loss versus frequency, and
- Input and output reflection coefficient (or VSWR) versus frequency.

Six different wiggly geometries and one parallel geometry were selected and several directional couplers for each geometry were fabricated, resulting in a total of 31 directional couplers.

Wiggly Phase Shifter

The wiggly phase shifter discussed in this paper is of the delay-line type. Five variables require definition for the fabrication of phase shifters:

- Optimum wiggly geometry,
- Conductor spacing,
- Optimum ratio of wiggly section length to wave length,
- Phase delay per unit length of wiggly section, and
- Phase delay per unit length of straight section.

Phase shifter performance is measured against three criteria:

- Number of degrees shifted versus frequency,
- Insertion loss versus frequency, and
- Input reflection coefficient (or VSWR) versus frequency.

Four different geometries were selected for evaluation, and five of each geometry were fabricated, giving a total of twenty phase shifters. Two of the geometries were wiggly type and the other two geometries were totally straight edge (meander) type.

Figure 2. Wiggly Directional Coupler Thin Film Network

Performance and Analysis

Wiggly Directional Coupler

Figure 2 shows the basic directional coupler TFN and defines the geometric parameters varied. Table 1 lists the dimensions for each of the TFNs.

All of the couplers were evaluated on the low frequency side of their coupling band. A summary of the coupler performance at 1 GHz is shown in Table 2, while Table 3 is a summary of the coupler band center performance.

If a small change in coupling across an operating frequency band can be tolerated, a significant space savings can be realized by operating the coupler on the low frequency side of its coupling band. Three conventional parallel line couplers are included in Tables 1, 2, and 3 for comparison. Several conclusions may be drawn from the data summarized in Tables 2 and 3.

- A 10 to 20 dB improvement in directivity results from wiggly coupler groups A, B, and E over the parallel coupler group P.
- A 30 percent increase in the effective dielectric constant is achieved by these same wiggly couplers, which allows a 15 percent smaller coupler length.
- An increase of approximately 7 percent in coupler band-width is realized by the wiggly coupler.

Further analysis of the measurement data shows that the best coupler band center characteristics are achieved with the geometry of wiggly coupler group B, while the best characteristics at the low frequency side of the coupler band are achieved by coupler group E. These couplers were chosen for further analysis. The significant geometric properties are listed in Table 4.

Table 1. Directional Coupler Dimensions Shown on Figure 2

Coupler Group	S (μm)	L (mm)	d (μm)	W (μm)
5 Units Group A*	83.9	17.8	254	686
4 Units Group B**	85.8	17.8	254	610
5 Units Group C**	84.2	14.0	254	686
5 Units Group D**	90.9	14.0	254	762
5 Units Group E**	83.1	14.0	178	610
4 Units Group F**	84.0	14.0	330	762
3 Units Group P***	84.8	20.3	---	494

*α of 90 degrees.

**α of 75 degrees.

***Parallel lines.

Table 2. Coupler Performance at 1000 MHz

Coupler Group	Coupling Loss and Insertion Loss (dB)	Isolation and Directivity (dB)	Input Reflection Coefficient and Effective Dielectric Constant
5 Units, Group A*	10.0 & 0.52	37.9 & 27.9	0.008 & 6.69
4 Units, Group B**	9.9 & 0.55	39.2 & 29.3	0.004 & 6.53
5 Units, Group C**	11.5 & 0.52	36.9 & 25.4	0.015 & ---
5 Units, Group D**	12.2 & 0.49	33.0 & 20.8	0.038 & ---
5 Units, Group E**	11.6 & 0.55	43.8 & 32.2	0.028 & 6.53
4 Units, Group F**	11.3 & 0.59	29.9 & 18.6	0.032 & ---
3 Units, Group P***	9.6 & 0.88	25.5 & 15.9	0.080 & 4.95

*α of 90 degrees.

**α of 75 degrees.

***Parallel geometry.

Figure 3. Wiggly Coupler E, Below Band Center

Figure 4. Parallel Coupler P, Below Band Center

Table 3. Coupler Performance at Center Frequency (F_c)

Coupler Group	Center Frequency (GHz) (F_c)	1 dB Bandwidth (Percent of F_c) and Input Reflection Coefficient	Insertion Loss and Coupling Loss (dB)	Isolation and Directivity (dB)
Wiggly Type Geometry				
5 Units, Group A*	1.630	67 & 0.012	0.88 & 8.6	38.1 & 29.5
4 Units, Group B**	1.650	65 & 0.024	0.89 & 8.5	43.8 & 35.3
1 Unit, Group E**	2.100	67 & 0.031	1.02 & 8.5	32.4 & 23.9
3 Units, Group P***	1.667	59 & 0.089	1.16 & 8.1	21.1 & 13.0

* α of 90 degrees.** α of 75 degrees.

***Parallel Geometry

Average values are listed where more than one coupler is of same geometry.

Sample plots of the data are shown in Figures 3 through 6 for visual comparison between the parallel line coupler and the two wiggly couplers, one from each of the two groups. The couplers chosen for comparison were selected on the basis of coupler spacing (S). The parallel line coupler chosen from group P had a spacing of 0.0757 mm, and the wiggly couplers closest to this spacing were chosen from each of the two groups (B and E). Wiggly coupler B had a spacing (S) of 0.0775 mm and was chosen for band center comparison, while wiggly coupler E had a spacing (S) of 0.0826 mm and was chosen for the low frequency side of the coupler band.

Both the parallel line coupler P and wiggly coupler B had the same band center frequency (1.65 GHz) even though the parallel line coupler was 14.3 percent longer (20.3 mm long compared to 17.8 mm long). The band center of wiggly coupler E was considerably higher (2.10 GHz) than P because the coupling length was only 14.0 mm long (coupler P was 45 percent longer than E).

Figure 5. Wiggly Coupler B, Band Center

Table 4. Geometry of Couplers Chosen for Analysis

Coupler Group	Sawtooth Depth (mm)	Coupling Line Width	
		Mean X (mm)	Ratio X/h
B*	254	483	0.70
E*	178	521	0.76

*The sawtooth angle (α) was 75 degrees and the total width was 610 mm.

Figures 3 and 4 compare the low frequency characteristics while band center characteristics are compared in Figures 5 and 6.

The relationship of line spacing and coupling length to the coupling characteristics is required to fabricate wiggly couplers to meet a specified coupling loss. The coupling is related to the even and odd mode characteristics impedances by:²

$$P = 10 \log \left(\frac{K^2 \sin^2 \theta}{1 - K^2 \cos^2 \theta} \right), \quad (1)$$

$$K = \frac{Z_{oe} - Z_{oo}}{Z_{oe} + Z_{oo}}, \quad (2)$$

$$\theta = \frac{\sqrt{E_{eff}}(F)(L)(2\pi)}{C} = \frac{\sqrt{E_{eff}}(F)(L)}{(47.713)(\text{GHz})(\text{mm})} \quad (3)$$

Figure 6. Parallel Coupler P, Band Center

where:

Z_{oe} = Even mode characteristic impedance,

Z_{oo} = Odd mode characteristic impedance,

θ = Electrical length of coupling section,

P = Power ratio of coupling in dB,

K = Coupling factor,

F = Frequency,

L = Coupling length,

E_{eff} = Effective dielectric constant,

C = Velocity of light, and

X = Mean wiggly line width.

The primary problem is in the determination of the even and odd mode impedances. Data is readily available for the parallel line coupler line geometry in microstrip.²

Because of the general nature of the microwave fields for the wiggly coupler, the even mode characteristic impedance is assumed to be essentially undisturbed from those of the parallel microstrip coupler. It is also assumed that the odd mode characteristic impedance of the wiggly coupler will follow the same general trend with conductor spacing as it does for the parallel microstrip coupler. Armed with these two assumptions, the odd mode characteristic impedance is calculated as follows:

$$Z_{oo} = Z_{oe} \left(\frac{1 - K}{1 + K} \right), \quad (4)$$

where

$$K = \sqrt{\frac{N}{N \cos^2 \theta + \sin^2 \theta}} \quad (5)$$

$$N = 10^{P/10}, \quad (6)$$

N = Linear power ratio of coupling,

and other quantities are as previously defined.

From this calculation and the above assumptions, a graph (Figure 7) was constructed of even and odd mode characteristic impedance for the two wiggly couplers of the chosen geometry. The best center band characteristics are achieved when x/h is 0.70 while the best characteristics below center band operation are achieved when x/h is 0.76. A partial check on the accuracy of this construction is shown in Figure 8 where a plot of the measured data of wiggly coupler E is superimposed upon a calculated curve. The calculated and measured data are very nearly in agreement.

Wiggly Phase Shifter

Four different phase shifters were fabricated on 0.686 mm thick alumina. These phase shifters are of

the delay-line type. Two phase shifters were wiggly delay lines, the only difference being in the length of the sawtooth pattern (C section) (Figure 9). The wiggly length of group B units was 20 percent longer than the wiggly length of group A units. The other two were meander line phase shifters, one with 1.905 mm line spacing (group C) and the other (group D) with a 0.953 mm line spacing. Five devices of each type were fabricated to check the consistency of production capability.

One of the group A units was measured with all three C sections in the circuit to establish the amount of

Figure 7. Even and Odd Mode Characteristic Impedance for Wiggly Directional Coupler

Figure 8. Wiggly Coupler E

phase shift obtained per unit length of wiggly C section. One wiggly C section was then removed from the circuit by removing a portion of the metalization at the base of the C section and adding a copper foil strip to complete the 50 Ω transmission line. Successive measurements were made with each of the three C sections removed.

The effective dielectric constant for the wiggly C section and the effective dielectric constant for the straight line portion of the phase shifter are both calculated from the measured data. The effective dielectric constant is given as follows:

$$\epsilon_{\text{eff}} = \left(\frac{c\theta}{2\pi LF} \right)^2 \quad (8)$$

$$\xi = (L_w)(F)(\sqrt{\epsilon_g})/C \quad (9)$$

where

ξ = Wavelengths in W-length

c = Velocity of light

ϵ_g = Effective dielectric constant at low frequencies ($\xi \leq 0.05$)

θ = Phase shift

L_w = W-length (Figure 9)

L_c = C-section length (Figure 9)

L = Physical line length

F = Frequency

Similar calculations of effective dielectric constant are made for the 1.905 mm and 0.953 mm spaced meander line phase shifters. The mean and standard deviations of these calculations are shown in Table 5. The effective dielectric constant of the meander lines is

Table 5. Effective Dielectric Constant

Type Line	Mean	Standard Deviation
C Section Wiggly Line	3.20	0.12
Straight Sided 50 Ω Line Interconnecting Cs	5.63	0.37
Meander 50 Ω Line With 75 Mil (1.905 mm) Spacing	5.54	0.02
Meander 50 Ω Line With 37.5 Mil (0.953 mm) Spacing	4.83	0.02

Figure 9. Wiggly Phase Shifter C-Section

not constant but varies with the frequency as shown in Figure 10. The apparent effective dielectric constant of the wiggly C section also varies with frequency and reaches a maximum of 7.3 at the frequency where the straight line length of the sawtooth portion would be one quarter wavelength long if the effective dielectric constant were the same as the low frequency value of 3.2 (ϵ_g). The non-linearity of the apparent dielectric constant (computed by Equation 8) can be seen in Figure 11 where it is plotted against ξ (computed by Equation 9).

The apparent increase in effective dielectric constant is a result of additional phase shifts caused by signal coupling at the base of the C section. Therefore the wiggly C sections should not be longer than 0.06 wavelength computed with an effective dielectric constant of 3.2 to avoid rapid changes in effective dielectric constant with frequency variations.

The amount of phase shift per unit length of wiggly length is dependent upon the frequency and is given by:

$$\frac{\theta}{L} = \frac{(2\pi\sqrt{\epsilon_{\text{eff}}})}{C} F = \frac{(21.473^\circ)}{(\text{GHz})(\text{cm})} F, \xi \leq 0.06 \quad (10)$$

where

$\frac{\theta}{L}$ = Phase shift per unit of physical length,

C = Velocity of light = 29.979×10^9 cm/s, and

F = Frequency.

In reviewing the wiggly phase shifter measurement data, the frequency of minimum reflection coefficient (and minimum VSWR) was considered significant. Table 6 summarizes the normalized frequency of minimum reflection coefficient and the 1.05:1 VSWR normalized frequency bandwidth for each of the phase shifter types. A comparison of the phase shifter VSWR characteristics as a function of frequency normalized to the frequency of 180 degrees phase shift is shown in Figure 12.

Figure 10. Meander Line Effective Dielectric Constant

Figure 11. Apparent Dielectric Constant of C-Section as a Function of Wave Lengths (E_{eff} 3.20)

Figure 12. VSWR Comparison of Phase Shifter Types (5 Units of Each Type)

The following conclusions can be drawn from the data summarized in Table 6 and shown in Figure 12.

- The VSWR bandwidth of the wiggly phase shifter is approximately twice that of the meander line phase shifter.
- The frequency of minimum VSWR occurs near the frequency of 180 degree phase shift for the wiggly phase shifter.

Table 6. Summary of Phase Shifter Characteristics

Variables	Couplers			
	Group A Short Wiggly	Group B Long Wiggly	Group C Meander Line 0.953 mm Spacing	Group D Meander Line 1.905 mm Spacing
Frequency of VSWR, minimum F/F_c	1.008	0.957	1.255	1.212
1.05:1 VSWR Band F_{low}/F_c	0.736	0.597	1.135	1.028
F_{high}/F_c	1.190	1.340	1.397	1.351
(Band Width) Percent	45	78	21	27

All frequencies are normalized to the frequency of 180 degrees of phase shift (F_c).

- The frequency of 180 degrees phase shift occurs outside the 1.05:1 VSWR band for both meander line phase shifters.

The wiggly phase shifter characteristics may depend on the number of wavelengths in the C section. The fractional wavelengths at the frequency of minimum VSWR were calculated using Equation 9. The results are shown in Table 7.

The fact that both wiggly delay lines had the same fractional wave length long (ξ) wiggly C sections at the frequency of minimum VSWR suggests that this value should be chosen for design center. The degrees phase shift resulting from the C section was 110 for both wiggly phase shifters at the frequency of minimum VSWR. Therefore, it is concluded that circuit layout for wiggly phase shifters should have a C section no longer than 0.06 wavelength at the center frequency, and a total phase shift of 110 degrees for all the C sections. The remaining desired phase shift should be achieved by meander lines at least 1.905 mm away from other conductors. Adjacent wiggly C sections should also be spaced 1.905 mm apart.

Conclusions

Packaging techniques have been developed for hybrid microcircuit directional couplers and phase shifters which improve their microwave characteristics and save 15 to 20 percent of the HMC space now required. A wiggly (sawtooth) TFN geometry is employed which

Table 7. Wave Lengths in Wiggly C Section ($E_g = 3.20$)

Computation	Group A	Group B
Length of C Section (L_c)	(L_c)	1.20 (L_c)
$\xi/(C\text{-Section})$	0.0508	0.0509
ξ Total C-Sections	0.3046	0.3053

effectively slows the odd mode propagation velocity to match the even mode velocity.

For directional couplers, the wiggly geometry results in improved directivity and increased effective dielectric constant. The overall directivity is increased by approximately 15 dB and may be increased at either the coupler center frequency or the low frequency side of the coupler band by approximately 20 dB. The increase in effective dielectric constant for the wiggly geometry allows a 15 percent smaller coupler.

The wiggly phase shifter has twice the VSWR bandwidth of the meander line phase shifter, and is centered at the 180 degree phase shift whereas the meander line minimum VSWR does not occur at the 180 degree phase shift. The wiggly phase shifter requires 20 percent less HMC space than does the meander line phase shifter.

The odd mode impedance for the wiggly coupler was determined, and coupling loss was related to the ratio of the wiggly spacing to substrate thickness. The effective dielectric constants were also determined for the wiggly coupler, parallel line coupler, wiggly C section of the phase of shifter, and for two spacings of meander line phase shifters.

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