PHASE VELOCITY COMPENSATION IN PARALLEL-COUPLED MICROSTRIP

Steven L. March

Compact Engineering Division, C.G.I.S.
1106 Bobbie Lane, Garland, TX 75042 USA

Abstract

Techniques for compensating the unequal even- and odd-mode phase velocities encountered in parallel-coupled microstrip are discussed. New results on the use of lumped and semi-lumped capacitors are presented. A newer geometry, a cross between suspended-substrate stripline and microstrip, can be used to manufacture quadrature couplers with improved, broadband directivity performance.

Because microstrip is inhomogeneous, the even- and odd-mode propagation velocities for a coupled pair of microstrip lines are not equal. This inequality manifests itself in quadrature directional couplers as poor directivity. The directivity performance becomes worse as the coupling is decreased or as the dielectric permittivity is increased. For example, a 10% difference in phase velocities reduces the directivity of a 10 dB coupler to 13 dB from its theoretical infinite value with equal phase velocities. On the other hand, a 10% error in either modal impedance,with equal phase velocities, reduces the directivity only to 26 dB. The corresponding figures for a 20 dB coupler are 2 dB and 26 dB, respectively.

Compensation Techniques

Several techniques are available to equalize or compensate for the inequality in the modal velocities of the coupled microstrip section. The "wiggly-line" coupler first proposed by Podell [1] suffers from a lack of pertinent design information.

The use of anisotropic substrates has also been suggested as a means to improve the performance of microstrip directional couplers [2] . To equalize the phase velocities, the parallel component of the permittivity tensor must be approximately twice the perpendicular component. This degree of anisotropy is virtually non-existent in practical microwave substrate materials, although a factor of 1.2 to 1.5 has been observed in exotic materials such as boron nitride.

Dielectric overlays [3] have also been used to equalize the modal phase velocities by increasing the odd-mode effective dielectric constant and slightly lowering the even-mode value. The presence of the overlay causes a reduction in the width and separation between conductors, if the even- and odd-mode impedances are to be maintained constant, which results in increased conductor and dielectric loss compared to a conventional device.

Capacitive Compensation

Analytically, the simplest device is one in which no velocity compensation is employed. Instead of equalizing the phase velocities, compensation is achieved by adding a pair of capacitors (Figure 1) at the ends of the coupled section. In the even-mode, the capacitors are nearly invisible;they effectively increase the odd-mode phase length. Schaller [4] and Kajfez [5] have determined that the physical length of the coupler should be a quarter of the even-mode wavelength at the center frequency and that the capacitors can be calculated from:

$$C = \frac{1}{4 \pi f_o Z_{oo} \tan \theta_o} \qquad (1)$$

where

$$\theta_o = \sqrt{e_{effo} / e_{effe}}\ \pi/2 \text{ radians} \qquad (2)$$

and e_{effe} and e_{effo} are the even- and odd-mode effective dielectric constants, respectively. In equation (1), Z_{oo} is the odd-mode impedance and f_o is the design center frequency.

The above equations are nearly true for tightly coupled devices. It has been found that they predict a center frequency lower than desired. After calculating the required value of capacitance from equation (1), the coupler should be shortened by an additional amount equal to:

$$\Delta\theta_e = \tan^{-1}(\pi f_o C Z_{oe}) \text{ radians} \qquad (3)$$

Figure 2 shows the isolation performance of a capacitively-loaded 5.7 dB coupler. The electrical and physical parameters of the coupler are given in Table I. For comparison, a conventional coupler would exhibit approximately 26.3 dB isolation at 2.0 GHz, decreasing to 20.6 dB at 4.0 GHz.

For more loosely coupled devices, equations (1) through (3) are no longer valid, but provide good starting points for optimization. For a 15.8 dB coupler (Z_{oe} = 59.79 ohms, Z_{oo} = 43.13 ohms) on a 25 mil thick alumina substrate (e_r = 9.9) with a conductor thickness of 0.2 mils, the following parameters were calculated: strip width (w) of 22.21 mils, conductor separation (s) of 21.09 mils, spacing between substrate and upper shield (h_2) of 500 mils, e_{effe} = 7.1854 and e_{effo} = 5.8320. From equations (1) through (3), the physical length of a capacitively-loaded coupler centered at 3.5 GHz should be 304.07 mils and the capacitors should be 0.082 pf. When checked using SUPER-COMPACT, the center frequency was too low and the directivity was poor. Using optimization, the capacitors were reduced to 0.07 pf and the electrical length to 261 mils. The optimized performance, together with that of the conventional coupler, is shown in Figure 3 (coupling) and Figure 4 (directivity). Note that the presence of the capacitors reduced the midband coupling from 15.8 dB to 15.1 dB, while dramatically increasing the directivity. The small values of capacitance can be achieved either by using interdigitated capacitor structures [6] or by the use of short sections of tightly coupled microstrip, i.e., semi-lumped capacitors. The characteristic impedance of these end segments should be maintained equal to that of the main coupled section.

The use of semi-lumped capacitors in lieu of the ideal 0.07 pf devices was also checked using computer-aided analysis. These results are also shown in Figures 3 and 4. The coupling has again tightened slightly. Also, the directivity has deteriorated, but is still vastly improved over the conventional coupler.

Pseudo-Suspended-Substrate Stripline

There is an interesting and viable technique to actually equalize the even- and odd-mode propagation velocities. It requires the introduction of a small air region directly below the substrate as shown in Figure 5. The structure now resembles a pseudo-suspended-substrate stripline.

A computer program was written and incorporated into SUPER-COMPACT to calculate the dispersive properties of the structure using Galerkin's method in the Fourier-transformed domain. From the program, the depth of the lower air region, h_L, required to equalize the modal propagation velocities was determined for various values of coupling for both 25 mil thick alumina substrates (e_r = 9.9) and 15 mil fused silica substrates (e_r = 3.78) at a center frequency of 3.5

Ghz. In addition, the condition, $Z_o = \sqrt{Z_{oe} Z_{oo}} = 50$ ohms, was imposed. The results, in which the conductor thickness was assumed to be zero, are shown in Figure 6 The two curves accurately follow two simple relationships:

$$h_L = 1.05\ k^{-0.523} \quad (e_r = 9.9,\ h = 25\ \text{mil}) \qquad (4)$$

$$h_L = 1.35\ k^{-0.763} \quad (e_r = 3.78,\ h = 15\ \text{mil}) \qquad (5)$$

in which k is the midband voltage coupling coefficient. The frequency dependence of h_L was also investigated. Although small, some frequency dependence to the optimum value of the lower air gap is, as expected, present. For a 15.8 dB coupler fabricated on 25 mil thick alumina, the optimum value of h_L varies from 1.9 mils at 0.1 GHz to 2.6 mils at 18.0 GHz.

The coupling versus frequency performance for the quasi-suspended-substrate stripline device and the conventional one are nearly identical, as shown in Figure 3. The directivity response (Figure 4) includes the effects of dielectric and conductor losses.

The introduction of the air layer beneath the substrate lowers the value of the "equivalent" effective dielectric constant used to calculate the physical length of the coupled section for a specified center frequency. Thus, the physical length will be longer than a conventional microstrip coupler designed for the same center frequency, coupling coefficient, and substrate material. While this at first might seem a disadvantage, the additional length will ease fabrication problems at millimeter-wave frequencies. Furthermore, the structure's lower effective dielectric constants will reduce the dielectric loss when compared to a conventional coupler using the same substrate and having identical even- and odd-mode impedance. Because the conductors are wider in the pseudo-suspended-substrate stripline geometry than in the conventional microstrip design, the new geometry will exhibit lower conductor loss for the same frequency.

Calculating Physical Length

The "equivalent" effective dielectric constant is the value from which the physical length of the coupled pair is determined. For a given center frequency, the guide wavelength is the wavelength in free-space divided by the square root of the "equivalent" effective dielectric constant, e_{eq}. Dell-Imagine [7] has proposed

$$\sqrt{e_{eq}} = \frac{Z_{oe}\sqrt{e_{effe}} + Z_{oo}\sqrt{e_{effo}}}{Z_{oe} + Z_{oo}} \qquad (6)$$

Others have suggested that the correct value is found from the arithmetic average of the modal phase velocities (APV), i.e.,

$$\sqrt{e_{eq}} = \frac{\sqrt{e_{effe}} + \sqrt{e_{effo}}}{2}$$

During the course of this study, it was concluded that the physical length calculated based upon the APV is more correct than the value calculated by the method due to Dell-Imagine; e_{eq} calculated from the latter is always larger than that calculated from equation (7). The difference becomes smaller as the relative permittivity of the substrate is reduced or as the coupling becomes looser. When the lines are completely decoupled and Z_{oe} equals Z_{oo}, the results are equal.

Conclusions

Small lumped capacitors, or their distributed equivalents, can be used to increase directivity in microstrip quadrature couplers. An alternate structure, employing a small air gap beneath the substrate, can be employed to equalize the phase velocities in coupled microstrip.

References

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6. J.L. Hobdell, Optimization of Interdigital Capacitors, IEEE Trans., Vol. MTT-27, Sept. 1979, pp. 788-791
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TABLE I

PARAMETERS FOR 5.7 DB COUPLERS

Parameter	Value
Even-Mode Characteristic Impedance (Z_{oe})-	88.83 ohms
Odd-Mode Characteristic Impedance (Z_{oo})--	28.14 ohms
Substrate Relative Permittivity (e_r) ----	9.9
Substrate Thickness (h) ----------------	25.0 mils
Conductor Width (w) --------------------	14.36 mils
Conductor Separation (s) ---------------	1.69 mils
Conductor Thickness (t) ----------------	0.2 mils
Center Frequency (f_o) ------------------	3.0 GHz
Even-Mode Effective Permittivity (e_{effe})-	6.7713
Odd-Mode Effective Permittivity (e_{effo})--	5.5194
"Equivalent" Effective Permittivity(e_{eq})-	6.1294
Physical Length (Conventional Design) ---	397.28 mils
Physical Length (Capacitively-Loaded) ---	348.92 mils
Lumped Capacitors (Where Required) ------	0.145 pf

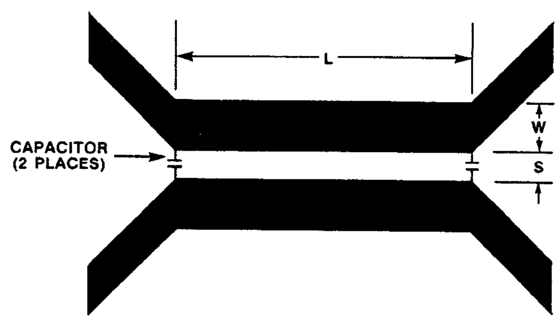

FIGURE 1 CONFIGURATION OF CAPACITIVELY-LOADED DIRECTIONAL COUPLER

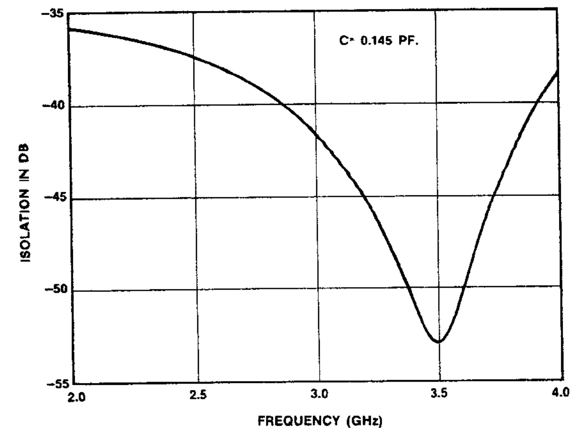

FIGURE 2 ISOLATION PERFORMANCE OF CAPACITIVELY-LOADED 5.7 DB MICROSTRIP COUPLER

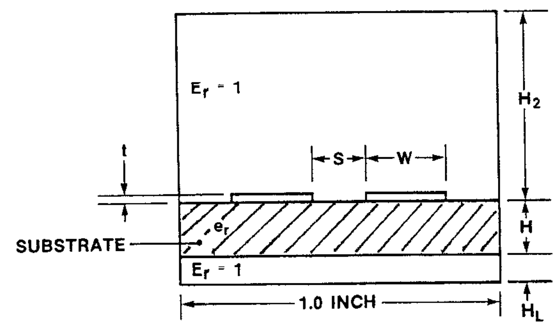

FIGURE 5 CONFIGURATION FOR PSEUDO-SUSPENDED-SUBSTRATE STRIPLINE

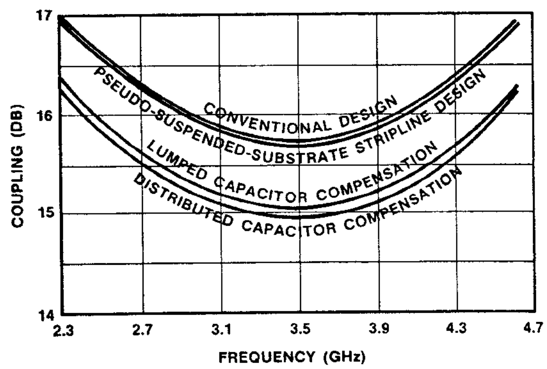

FIGURE 3 15.7 DB COUPLER DESIGN PERFORMANCE

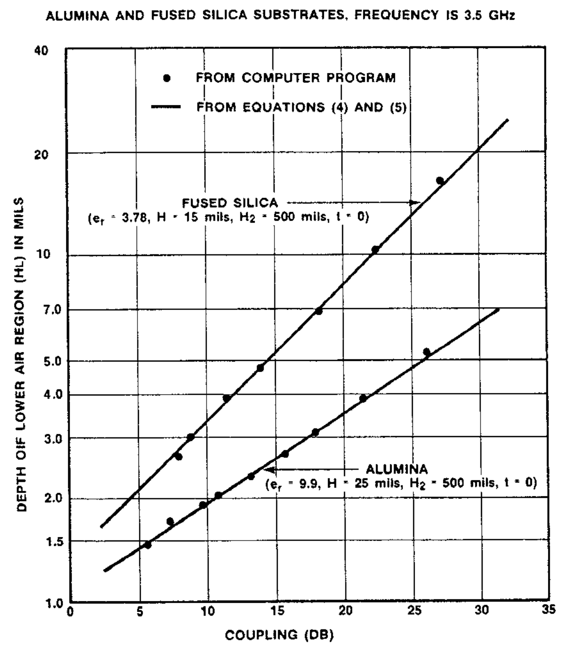

FIGURE 6 DEPTH OF LOWER AIR REGION VERSUS COUPLING

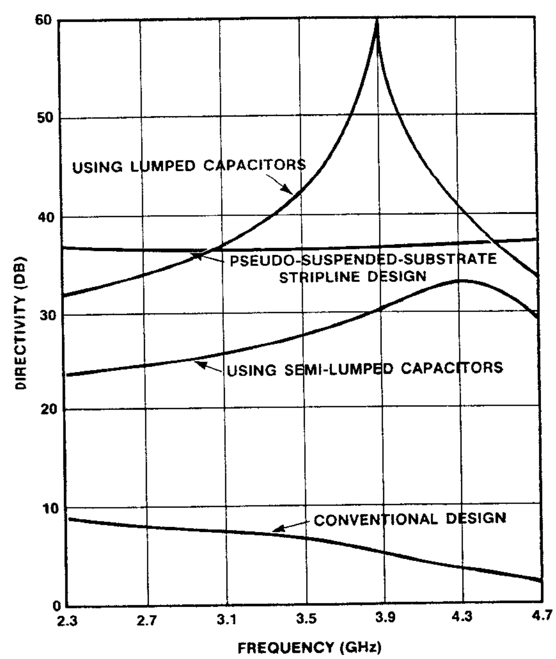

FIGURE 4 DIRECTIVITY PERFORMANCE OF 15.7 DB COUPLERS