SYNTHESIS AND DESIGN OF WIDEBAND SYMMETRICAL NONUNIFORM DIRECTIONAL COUPLERS FOR MIC APPLICATIONS

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ABSTRACT

A computer aided synthesis design procedure for wideband symmetrical nonuniform directional couplers in inhomogeneous media is presented. Solutions for the potential problems inherent to these couplers are given. Results for a 2-18 GHz 5-section, -3 dB nonuniform tandem directional coupler designed and built on alumina substrate are presented.

INTRODUCTION

Directional couplers are used in a variety of circuits including balanced mixers, balanced amplifiers and phase shifters. Several problems are encountered in the multioctave realization of directional couplers in microstrip. Wideband performance can be obtained with nonuniform couplers. The theory and design of TEM-mode symmetrical nonuniform couplers for wideband performance is well established in the literature (1,2). Very little has been done on the symmetrical nonuniform directional couplers in inhomogeneous media. Among the many reasons are the poor isolation and the practical realizability of tight coupling values.

A planar technique for phase velocity compensation has been reported by Podell (3). Podell uses a wiggly coupled structure and relies on a trial and error method to achieve an acceptable level of isolation. A semi-empirical method to compute the wiggle depth is presented in this paper.

An interdigitated nonuniform coupler is used to realize tight coupling values. With this new nonuniform structure, two couplers in tandem (4) would be sufficient to design -3 dB, multioctave bandwidth directional couplers in microstrip.

At present, a direct synthesis of physical parameters of nonuniform directional couplers is not possible. As an approximation, the uniform coupled-line shape ratios are assumed to be valid at each elemental section of the nonuniform lines. A simple, fast and accurate technique in the form of cubic splines (5) is given.

SYNTHESIS PROCEDURE

A. Generation of Cubic Splines

The coupled-line even- and odd-mode characteristic impedances are given by

$$Z_{oe} = \frac{1}{c\sqrt{C_e\, C_{ea}}} \qquad (1)$$

$$Z_{oo} = \frac{1}{c\sqrt{C_o\, C_{oa}}} \qquad (2)$$

where c is the speed of light, C_e and C_o are the even- and odd- mode capacitances and C_{ea} and C_{oa} are the corresponding capacitances with dielectric replaced by air.

From (1) and (2)

$$Z_{oe}\, Z_{oo}\, c^2\sqrt{C_e\, C_{ea}\, C_o\, C_{oa}} - 1 = 0 \qquad (3)$$

or using $Z_o^2 = Z_{oe}\, Z_{oo}$, we have,

$$Z_o^2\, c^2\sqrt{C_e C_{ea}\, C_o\, C_{oa}} - 1 = 0 \qquad (4)$$

Equation (4) is now a function of w/h, S/h and ε_r of the substrate. The realizability condition for a directional coupler is that $Z_{oe} \geqslant Z_{oo}$ for all coupling values. Keeping this in mind, equation (4) can easily be optimized for a given set of values of S, to yield the corresponding set of values for w and cubic splines w(k), s(k) (k being the coupling coefficient) formed for specified Z_o, ε_r and h.

Cubic splines. The idea of using spline is to use different polynomials to connect adjacent points, piecing them together smoothly instead of trying to make one polynomial go through all the points. Hence, for a given N-data, we have N-1 polynomials. A cubic spline has the following general form

$$g_i(x_i) = a_i x^3 + b_i\, x^2 + c_i\, x + d_i \quad i = 1,2,..,N-1,$$

with $g_i(x)$ defined in the interval between x_i and x_{i+1}.

For given x points and y values, the spline must touch the points giving $g_i(x_i) = y_i$ and $g_i(x_{i+1}) = y_{i+1}$ for i = 1,2,...,N-1. Spline curves smoothly around the points; therefore the first derivatives of the spline polynomials must be equal at the points. If P_i is the value of the second derivative of the spline at x_i, then all of the a,b,c,d coefficients can be computed for the spline segments since there will result four equations in four unknowns for each spline segment with $P_1=P_N=0$.

Hence for $i = 1,2,...,N-1$, we must have

$$g_i(x_i) = y_i \ , \quad g_i(x_{i+1}) = y_{i+1} \ ,$$

$$g''_i(x_i) = P_i \ , \quad g''_i(x_{i+1}) = P_{i+1} \ .$$

B. Phase Velocity Compensation

The difference in the even- and odd- mode phase velocities causes a degradation in directivity of the directional couplers. The odd-mode phase velocity can be slowed down to be equal to the even-mode phase velocity by providing extra distance for the odd-mode wave to travel. This can be done by wiggling the inner edges of the conductors as shown in Fig.1. To determine the wiggle depth, d, consider the odd-mode capacitance without wiggling:

$$C_o = C_{pf} + C_{fo} \tag{5}$$

where $C_{pf} = C_p + C_f$, C_p is the capacitance between the conductor and the ground plane, C_f is the fringing capacitance of a single line and C_{fo} is the capacitance between the conductors both in air and dielectric.

The odd-mode capacitance with wiggle is given approximately by

$$C_{wo} = C_{pf} + C'_{fo} \tag{6}$$

Only C_{fo} is assumed to be affected. Now, for $v_e = v_{ow}$ with wiggle, we need $\varepsilon_{re} = \varepsilon_{row}$. To accomplish this, the odd-mode capacitance has to be increased by a factor given by the ratio $\varepsilon_{re}/\varepsilon_{ro}$. Hence,

$$\frac{\varepsilon_{re}}{\varepsilon_{ro}} C_o = (C_{pf} + C_{fo}) \frac{\varepsilon_{re}}{\varepsilon_{ro}} \tag{7}$$

From (6) and (7)

$$C'_{fo} = C_{fo} \left(\frac{\varepsilon_{re}}{\varepsilon_{ro}} - 1\right) + \frac{\varepsilon_{re}}{\varepsilon_{ro}} C_{fo} \tag{8}$$

Equation (8) gives the capacitance per unit length between the conductors for the wiggly structure. The ratio C'_{fo}/C_{fo} is the factor by which the odd-mode length will be increased. Using the wiggle parameters given in Fig.1 we can deduce that

$$\frac{\ell_w}{\Delta x} = \frac{C'_{fo}}{C_{fo}} \tag{9}$$

The wiggle depth, d, is then given by

$$d = \frac{\Delta x}{2} \sqrt{\left(\frac{C'_{fo}}{C_{fo}}\right)^2 - 1} \tag{10}$$

Cubic spline for wiggle depth d versus coupling coefficient k, d(k), can be constructed for the same specified z_o, ε_r and h.

C. Synthesis of Coupling Distribution

To determine the continuous physical parameters W(x) and S(x) for the nonuniform directional coupler, we need to find k(x), the variation of coupling coefficient along the coupler length. k(x) can be synthesised for a specified coupling, by using the fundamental non-uniform coupled line synthesis functions given in (2). The inhomogeneous media require the application of the even- and odd-modes separately and the required performance is obtained by the superposition of the two modes. The continuous coupling coefficient is then given by

$$k(x) = \frac{Z_{oe}(x) - Z_{oo}(x)}{Z_{oe}(x) - Z_{oo}(x)} \tag{11}$$

2-18 GHz, 5-SECTION, -3dB TANDEM COUPLER ON ALUMINA

A step by step procedure is given below:

1. Set initial specifications:

   Z_o = 50 Ohm, ε_r = 9.9, h = 635 μm.

2. Select capacitance formulation.

   The even- and odd-mode capacitance analyses of J.I. Smith (6), and Garg et al (7) are used. The odd-mode capacitance is found to be converging (diverging) fast when Smith's method (Garg et al) are used. Extensive comparison with other available data for 2- and 4-coupled lines (8,9) is made by taking the arithmetical average of the individual capacitances evaluated by these methods and excellent agreement is found.

3. Set number of conductors, N = 2 and optimize equation (4) for a given set of values of s (strip spacing) to yield the corresponding values of w (strip width). About 30 values ranging from 1800 μm to 30 μm would be sufficient.

4. Construct cubic splines: Figs.2-4.

5. Compute v_e, v_o and length ℓ_c at the centre frequency, f_c= 10 GHz.

6. Compute wiggle depth d with Δx = 0.1 mm, for phase velocity compensation.

7. Include dispersion (Getsinger's formulation for coupled lines (10)) and repeat steps 3-6.

8. Repeat steps 3-7 with N = 4.

9. Specify coupled output $|C_1(W)|$. $|C_1(w)|$ is the coupling response of each of the couplers in tandem. A second order coupling value (1) will be used i.e. $|C_1(w)|$ = 0.4144.

10. Synthesize k(x) at selected intervals Δw = 0.1, Δx = 0.05 mm with $v_e = v_o = 97.3 \times 10^9$ mm/s with $\ell = (n + 1)\ \ell c$ = 14.6 mm (n is the number of sections).

11. Optimize for equal ripple performance. The difference curve between the computed performance and ideal output is formed in the design bandwidth (2-18 GHz) and this curve is added on $|C_1(w)|$ to form the new 'input' function.

12. Repeat step 10 to determine k(x) distribution shown in Fig.5.

13. Compute w(x), s(x) and d(x) by evaluating w(k), s(k) and d(k) respectively at all values of k(x) (from-$\ell/2$ to 0.0 because of symmetry) both for N = 2 and 4. These are shown in Fig.6.

The -3 dB nonuniform tandem directional coupler is built using conventional photolithography processes and etching the final circuit on 1" x 1" x 0.025" alumina substrate. Short lengths of 0.025 mm diameter gold bond wires are used to provide the crossovers. The mask and photograph of this design are given in Fig.7.

MEASURED RESULTS

Measurements are carried out on an Automatic Network Analyser HP8510. The measured performance is shown in Fig.8. The measured coupled ports given in Fig. 8(a), are in balance in the 2-17 GHz band. The ripples and the sharp drop after 17 GHz are caused by the bond wires used to connect the alternative lines at the centre. The measured maximum return loss is -15 dB in the same bandwidth. Isolation is observed to be somewhat constant and follows the return loss with a measured maximum value of -15 dB. The measured return loss and isolation are given in Fig.8(b) and (c) respectively. The phase deviation from quadrature is ± 12 in the 2-18 GHz band and is shown in Fig. 8(d). The 3.5 mm OSM type launchers used for coaxial-to-microstrip and microstrip-to-coaxial transitions and the gold bond wires used for crossovers, contribute to the coupler insertion loss. Fig.8(e) is a measure of coupler balance and insertion loss for a typical reflection type phase shifter application. This is obtained by open circuited coupled ports (reference from the substrate edge); the signal re-entering the coupler cancels out at the input port and add up at the isolated port.

CONCLUSIONS

A computed aided synthesis design procedure in the form of cubic splines is developed for non-uniform directional couplers in inhomogeneous media. A four finger interdigitated nonuniform coupler is designed in order to realize tighter coupling values at the centre. Isolation is greatly improved over the conventional design by wiggling the inner edges of loosely coupled sections. Bond wires have a significant effect on the overall coupler performance and several of them are required to achieve the desired performance.

Multioctave performance of a nonuniform directional coupler in inhomogeneous media has been demonstrated.

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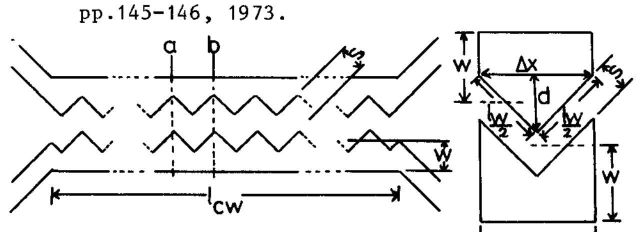


Fig.1. Wiggly coupled line parameters.

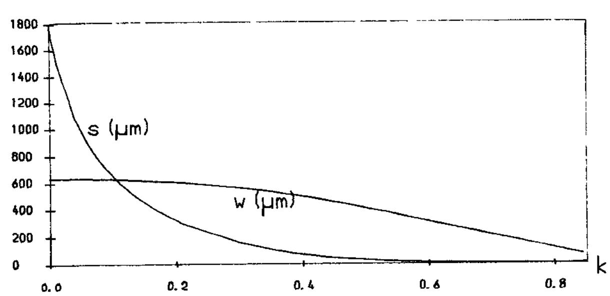


Fig.2. Cubic splines for 2 coupled lines at f=0.0.

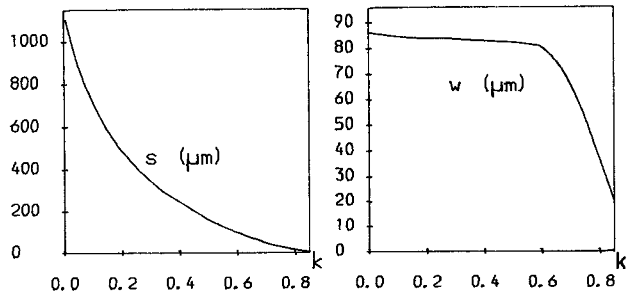


Fig.3. Cubic splines for interdigitated coupler at f = 0.0 .

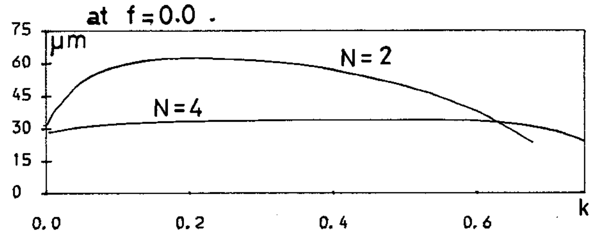


Fig. 4. Computed wiggle depth with Δx = 0·1mm

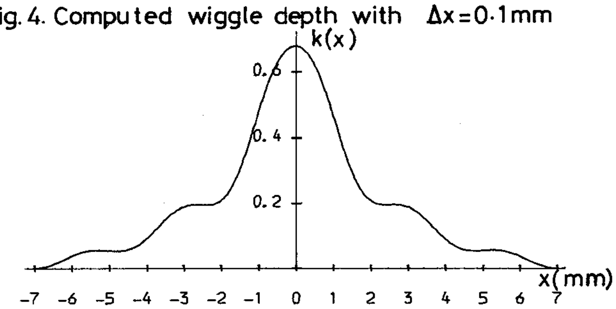


Fig. 5. k(x) for 5-section, -8·34 dB coupler.

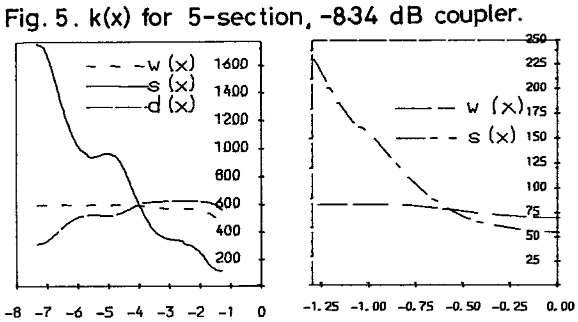
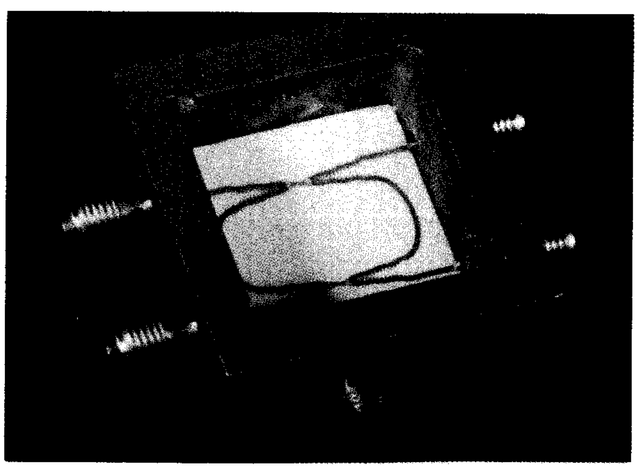


Fig.6. Continuous physical parameters.



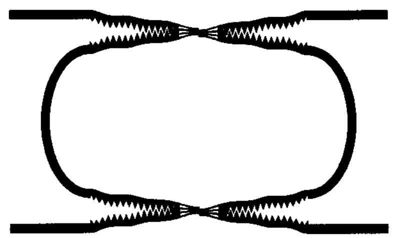


Fig.7. Mask and photograph of -3 dB tandem coupler.

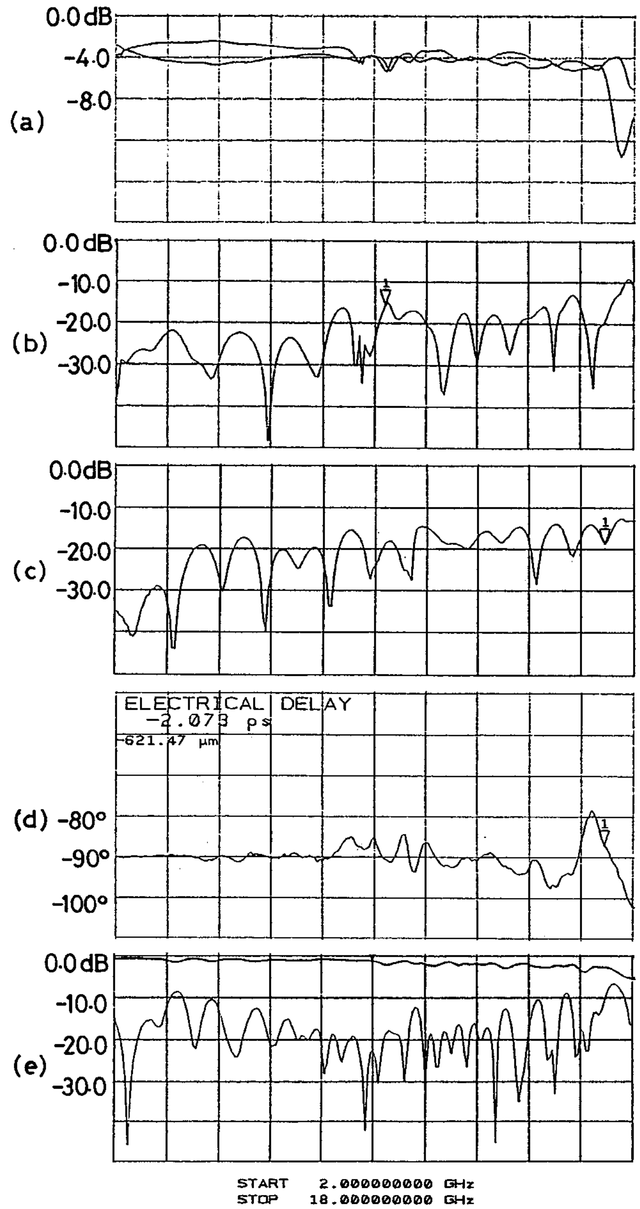


Fig.8. Measured coupler performance, (a) Coupled ports, (b) Return Loss, (c) Isolation, (d) Phase difference between coupled ports, and (e) Measured isolated port with open circuited coupled ports.