Synthesis, Design, and Construction of Ultra-Wide-Band Nonuniform Quadrature Directional Couplers in Inhomogeneous Media

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Abstract—**A computer-aided synthesis design procedure is given for nonuniform quadrature directional couplers in inhomogeneous media. A wiggly geometry is employed which effectively slows the odd-mode phase velocity to match the even-mode phase velocity. The wiggly geometry results in improved isolation and increased effective dielectric constant. This technique provides a shorter coupler length due to increased effective dielectric constant.**

Cubic splines of strip width, strip spacing, and wiggle depth as functions of coupling coefficient are computed using static capacitances of uniform coupled lines. These functions are then used as synthesis functions to evaluate the continuous physical parameters of nonuniform coupled lines by using the continuously varying coupling coefficient. A nonuniform interdigitated coupler is introduced to realize the tight coupling values.

Manufacturing tolerances on wiggle depth are derived. Geometrical details are given for the construction of nonuniform wiggly lines. Computational and experimental data are also given for a 2–18 GHz, −3 dB tandem nonuniform directional coupler built on alumina substrate.

I. Introduction

THE THEORY and design of TEM-mode symmetrical nonuniform directional couplers using the nonuniform transmission line analogy is well established in the literature [1]–[3]. Asymmetrical nonuniform microstrip couplers have also been reported for wide-band operation [4], [5]. A computer-aided synthesis design procedure for symmetrical nonuniform microstrip couplers has been reported by Uysal *et al.* [6].

In the case of wide-band symmetrical nonuniform directional couplers in inhomogeneous media, it is of primary importance to determine the continuous w/h and s/h (where w is line width, s is line spacing, and h is the substrate thickness) as accurately as possible. At present a direct synthesis of physical parameters is not available. Instead, the uniform coupled lines data are assumed to be valid at each elemental section of the nonuniform coupled lines. However a synthesis technique to determine the physical parameters of uniform microstrip couplers for the entire range of coupling values ($0 \leqslant k \leqslant 1$) is not available in the literature. Extensive work has been done by many authors [7]–[9] on the analysis of coupled lines and an approximate synthesis method has also been reported by Akhtarzad *et al.* [10] for moderate coupling values. In fact, the practical difficulties in the realization of extremely small strip spacing for tight coupling values made useless the extension of design equations to cover the entire coupling range. The invention of the interdigitated coupler by Lange (thereafter called the Lange coupler) [11] as an alternative for the realization of tight coupling (such as −3 dB) in microstrip within reasonable practical limits led to different forms and design approaches. Presser [12], Paolino [13], Kajfez *et al.* [14], and Rizzoli *et al.* [15] have reported interdigitated couplers for coupling values other than −3 dB. In this paper a simple computer-aided synthesis method based on static capacitances and valid for any even number of coupled lines is presented. Cubic splines [16] are formed for the computed physical parameters versus coupling coefficient to form the synthesis functions. The physical geometry of the nonuniform coupled lines is completely defined by evaluating these cubic splines at all values of continuous coupling coefficient obtained from the synthesis of nonuniform coupled lines for a specified nominal coupling. The results for given line-parameter ratios computed in this paper for double- and quadruple-coupled lines on alumina substrate are in excellent agreement with other published data in the literature. Other factors which affect the coupler performance, such as dispersion, can easily be included in the synthesis procedure.

The inhomogeneity of the microstrip configuration will result in different mode velocities, causing a degradation in the circuit function by a significant loss of directivity. With uniform coupled lines several methods can be used for phase velocity compensation [17], [18]. However, these techniques cannot easily be applied to nonuniform lines because the methods used are functions of coupling coefficient. An entirely planar compensation technique has been reported by Podell [19]. In this paper a semiempirical phase velocity compensation for nonuniform directional couplers using Podell's wiggly line technique is presented.

Design information for the nonuniform wiggly lines will be given in detail.

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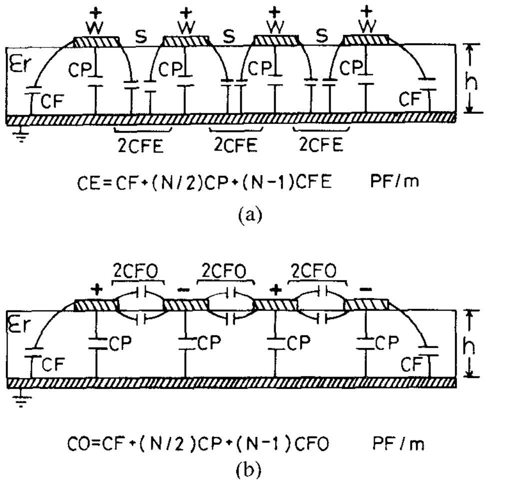

Fig. 1 The N-coupled-line static capacitance parameters. (a) Even mode. (b) Odd mode.

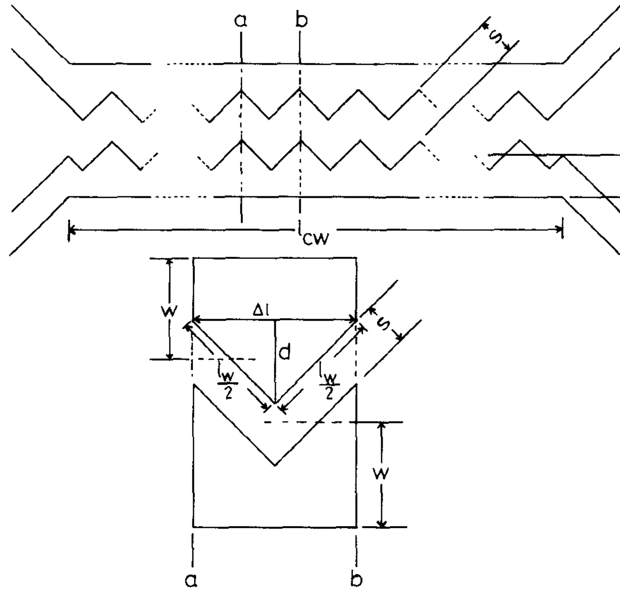

Fig. 2. Wiggly coupled line parameters.

II. Synthesis Procedure

A. Generation of Cubic Splines

The N-coupled-line static capacitance parameters are shown in Fig. 1. Here N is the number of conductors and we shall assume that this model is valid for an even number of coupled microstrips. The even- and odd-mode characteristic impedances can be related to the static capacitances as follows:

$$Z_{0e} = \frac{1}{c\sqrt{C_e C_{ea}}} \tag{1}$$

$$Z_{0o} = \frac{1}{c\sqrt{C_o C_{oa}}} \tag{2}$$

where c is the speed of light in vacuum, C_e and C_o are given in Fig. 1, and C_{ea} and C_{oa} are the corresponding capacitances with dielectric replaced by air.

From (1) and (2), we have

$$Z_{0e} Z_{0o} c^2 \sqrt{C_e C_{ea} C_o C_{oe}} - 1 = 0 \tag{3}$$

or using $Z_0^2 = Z_{0e} Z_{0o}$,

$$Z_0^2 c^2 \sqrt{C_e C_{ea} C_o C_{oa}} - 1 = 0. \tag{4}$$

Equation (4) is valid for zero frequency only. The dispersion formulas given by Getsinger [20] can be used in (4). Then

$$Z_0^2 c^2 C_{ea} C_{oa} \sqrt{\epsilon_{re}(f)\epsilon_{ro}(f)} - 1 = 0. \tag{5}$$

The even- and odd-mode capacitances of a coupled pair of microstrip lines can be expressed as functions of the shape ratios w/h and s/h and dielectric constant ϵ_r [21], [22]. Therefore (5) becomes a function of Z_0, ϵ_r, h, w, s, and f. From the designer's point of view ϵ_r, h, Z_0, and the design center frequency are all known. For a given Z_0, there is only a single pair of shape ratios $(w/h, s/h)$ which satisfy Z_0 and the amount of coupling required simultaneously. Therefore, for a given value of s, (5) can be optimized to yield the corresponding value of w. For a realizable directional coupler we must have $Z_{0e} \geqslant Z_{0o}$. This condition can be used to determine the value of w for a given s over the entire range of the coupling coefficient $(0 \leqslant k \leqslant 1)$. This means that at a given design center frequency the value of s will converge to a finite value s_1 for $k = 0$; i.e., the values of s higher than s_1 will give negative coupling coefficients $(Z_{0o} > Z_{0e})$. The optimized shape ratios can now be defined as functions of coupling coefficients $w(k)$ and $s(k)$ by the use of cubic splines [16].

B. Phase Velocity Compensation

The odd-mode phase velocity can be slowed down to be equal to the even-mode phase velocity by wiggling the inner edges of the conductors as shown in Fig. 2.

The odd-mode capacitance without wiggling is given by

$$C_o = C_{pf} + C_{fo} \tag{6}$$

where $C_{pf} = C_p + C_f$. The odd-mode capacitance with wiggle is given by

$$C_{ow} = C_{pf} + C'_{fo}. \tag{7}$$

We have assumed that wiggling affects the capacitance between the conductors only. To equalize even- and odd-mode phase velocities we need $\epsilon_{re} = \epsilon_{row}$. To achieve this, the odd-mode capacitance has to be increased by a factor $\epsilon_{re}/\epsilon_{ro}$. Multiplying (6) by this factor and equating it to (7), we can solve for C'_{fo}:

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

This is the capacitance per unit length between the conductors for the wiggly coupled lines. The odd-mode length will then be increased by the factor C'_{fo}/C_{fo}. From Fig. 2 the wiggle length can be deduced as

$$l_w = \Delta l \frac{C'_{fo}}{C_{fo}}. \tag{9}$$

The wiggle depth d is then given by

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

The derivation of (10) is based on the assumption that only C_{fo} is affected. However this is not true for loose coupling values since both C_{fo} and C_{fe} approach C_f and have the same order of magnitude. Therefore, the even-mode capacitance will also be increased. This can be corrected by an additional reduction in the even-mode length while keeping the same wiggle depth. The coupler length is then given by

$$l_{2c} = l_{cw}\sqrt{\frac{C_{pf}+C_{fe}}{C_{pf}+C'_{fe}}} \tag{11}$$

where

$$C_{pf} = C_p + C_f \qquad C'_{fe} = C_{fe}\frac{C'_{fo}}{C_{fo}}$$

and

$$l_{cw} = \frac{\lambda_e + \lambda_{ow}}{8}$$

with λ_e the even-mode wavelength and λ_{ow} the odd-mode wavelength with wiggly coupled lines.

C. Nonuniform Coupler Synthesis

To determine the continuous 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. The inhomogeneous media require the application of the even and odd modes separately to the fundamental nonuniform coupled-line synthesis functions [2], [3]. The required performance can then be obtained by the superposition of the two modes. The continuous coupling coefficient is then given by

$$k(x) = \frac{Z_{0e}(x) - Z_{0o}(x)}{Z_{0e}(x) + Z_{0o}(x)}. \tag{12}$$

Once $k(x)$ is determined, $w(x)$ and $s(x)$ can be formed by evaluating $w(k)$ and $s(k)$ cubic splines, respectively, at all values of $k(x)$.

III. Computations of Cubic Splines for Double- and Quadruple-Coupled Lines on Alumina Substrate

The even- and odd-mode static capacitance parameters for N-coupled microstrip lines are defined in Fig. 1. Closed-form expressions for the individual capacitances in terms of strip width, strip spacing, dielectric constant, and substrate thickness have been reported by Smith [21] and Garg *et al.* [22]. Computer subroutines are written to compute the individual capacitances given by [21] and [22]. Equation (5) with $f = 0$ is then used to optimize the shape ratios of N-coupled microstrip lines. The optimization routine requires Z_0, ϵ_r, h, N, and a set of values of s as input. The computations are carried out with $Z_0 = 50\ \Omega$, $\epsilon_r = 9.9$, $h = 635\ \mu$m, and $N = 2$ ($N = 4$) and for a given set of values of s. It is found that some of these capacitances converge or diverge fast. The arithmetical averages of these capacitances are formed and the corresponding shape ratios are then computed and compared with other available data for $N = 2$ [8], [9] and $N = 4$ [12]–[15]. The shape ratios computed with the arithmetical averages of the capacitances given in [21] and [22] are found to be in excellent agreement with other available data. The next step is the construction of cubic splines $w(k)$, $s(k)$, and $d(k)$. About 30 values of s ranging from 1800 μm to 30 μm would be sufficient to construct the cubic splines of the form shown in [6, figs. 2–4].

IV. 2–18 GHz, Five-Section, −3 dB Tandem Coupler on Alumina

A. Determination of k(x)

With phase velocity compensation the even- and odd-mode velocities are equal. However, wiggling cannot be applied directly to the interdigitated coupler. The midband coupling length for double coupled lines can be determined by using (11). The midband coupling length for the interdigitated coupler is given by

$$l_{4c} = \frac{v_{4e} + v_{4o}}{8 f_c} \tag{13}$$

where v_{4e} and v_{4o} are the even- and odd-mode phase velocities of the interdigitated coupler and f_c is the midband frequency. For the five-section design, the nonuniform coupler length [2] is taken as

$$l = 5 l_{2c} + l_{4c} \tag{14}$$

where l_{2c} is given by (11).

To evaluate $k(x)$, the coupler center will be taken at $x = 0$. The reflection coefficient distribution function given in [3] is then modified as follows:

$$P_{e,o}(x) = \begin{cases} -\dfrac{2}{\pi v}\displaystyle\int_0^{2\omega_c} C(\omega)\sin\frac{2\omega x}{v}\,d\omega, & -\dfrac{l}{2} \leqslant |x| \leqslant -\dfrac{l_{4c}}{2} \\ -\dfrac{2}{\pi v_{4e,o}}\displaystyle\int_0^{2\omega_c} C_{e,o}(\omega)\sin\frac{2\omega x}{v_{4e,o}}\,d\omega, & -\dfrac{l_{4c}}{2} \leqslant x \leqslant \dfrac{l_{4c}}{2} \end{cases} \tag{15}$$

where the subscripts e and o denote the even and odd modes, respectively, ω_c is the design center frequency, and $C(\omega)$ is the desired coupling.

For a nominal −8.34 dB coupling, a second-order coupling value of $|C(\omega)| = 0.4144$ is needed. The coupler length is divided into equal elemental sections of $\Delta x = 0.05$ mm. The coupling is divided into elemental values of $\Delta\omega = 0.1$. The coefficient $k(x)$ is computed with $v_{2e} = v_{2o} = v = 97.3\times10^9$ mm/s, $v_{4e} = 111\times10^9$ mm/s, and $v_{4o} = 121\times10^9$ mm/s.

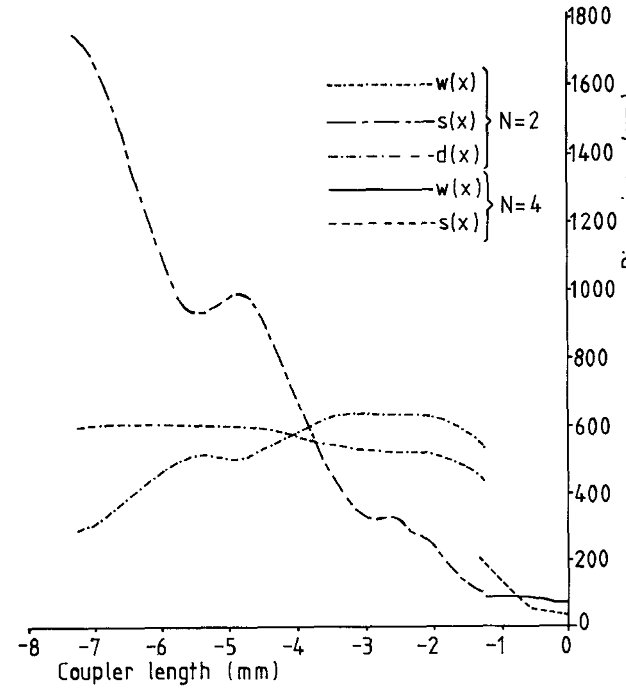

Fig. 3. The continuous physical parameters $w(x)$, $s(x)$, and $d(x)$ for a five-section, −8.34 dB coupler.

The optimized coupling coefficient $k(x)$ is given in [6, fig. 5]. Cubic splines $w(k)$, $s(k)$, and $d(k)$ are then evaluated at all values of $k(x)$ to form $w(x)$, $s(x)$, and $d(x)$, respectively. The continuous physical parameters are given in Fig. 3.

B. Correction for Wiggle Depth

Very small conductor spacings and line widths cannot be achieved by ordinary manufacturing techniques. We shall define the limits on conductor spacing and line width as s_{tol} and w_{tol}, respectively. Since the wiggle depth is continuously varying along the coupler length, each resultant wiggle will have different tolerances. To illustrate this the axial length Δl of each wiggle section is subdivided into m sections as shown in Fig. 4(c). The elemental subsections which correspond to w_{tol} are $m/2$ and $m/2+1$, and the corresponding subsections of s_{tol} are the first and the mth subsections. By using Fig. 4(c) we can derive the manufacturing tolerances on the wiggle depth d due to the practical limitations on line width and spacing as follows:

$$d_{\text{tol}\,w_j} = \frac{\left(\dfrac{d_{m/2}+d_{m/2+1}}{2}\right) w_{\text{tol}}}{\Delta x} \tag{16a}$$

and

$$d_{\text{tol}\,s_j} = \frac{\left(\dfrac{d_1+d_m}{2}\right) s_{\text{tol}}}{\Delta x}, \qquad j = 1,2,\cdots,\frac{\frac{l_{cw}}{2}}{\Delta l} \tag{16b}$$

where $d_{\text{tol}\,w}$ and $d_{\text{tol}\,s}$ are the corrections on wiggle depth due to manufacturing limitations on line width and spac-

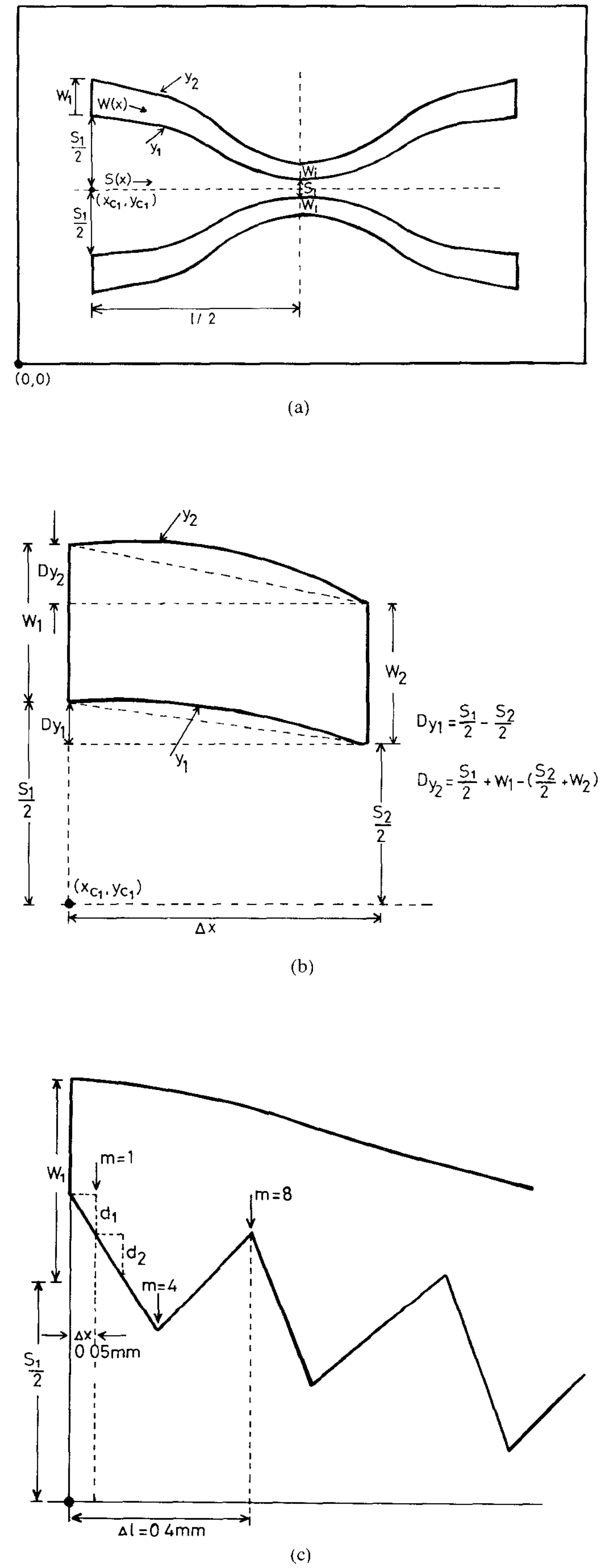

Fig 4. (a) Nonuniform coupler coordinate system. (b) Elemental section of nonuniform coupler. (c) Wiggly nonuniform coupler.

ing, respectively. The total correction factor is

$$d_{\text{tol}_j} = d_{\text{tol}\,w_j} + d_{\text{tol}\,s_j}.$$

The new wiggle depth d is given by

$$d_i' = d_i + \frac{d_{\text{tol}_j}}{\frac{m}{2}}, \qquad i = 1, \cdots, \frac{\frac{l_{cw}}{2}}{\Delta x}. \tag{17}$$

With $\Delta x = 0.05$ and $\Delta l = 0.4$, we have $m = 8$. For the computations $w_{\text{tol}} = 30\ \mu\text{m}$, $s_{\text{tol}} = 30\ \mu\text{m}$ are taken.

C. Nonuniform Coupler Geometry

The coordinate system of the nonuniform coupler is shown in Fig. 4(a). To define the entire geometry of the nonuniform coupler, we need to derive equations for the inner and outer edges of the coupled lines. The coupler has even symmetry at both $x = l/2$ and $y = y_{c_1}$. Therefore we shall consider only the upper half section of the coupler. The equations defining the geometry will first be derived without wiggling, and then wiggling will be introduced into the equation defining the inner edge of the conductor. Referring to Fig. 4(a) and (b), equations for $y_{1_{ij}}$ and $y_{2_{ij}}$ in terms of s_i and w_i can be expressed as

$$y_{1_{ij}} = (x_{c_i} - xo_{ij}) q_{1_i} + y_{c_1} + \frac{s_i}{2} \tag{18}$$

$$y_{2_{ij}} = (x_{c_i} - xo_{ij}) q_{2_i} + y_{c_1} + w_i + \frac{s_i}{2}. \tag{19}$$

Here q_{1_i} is the slope of the inner edge of the coupled line:

$$q_{1_i} = \frac{Dy_{1i}}{\Delta x} = \frac{s_i - s_{i+1}}{2\,\Delta x}$$

q_{2_i} is the slope of the outer edge of the coupled line:

$$q_{2_i} = \frac{Dy_{2i}}{\Delta x} = \frac{\frac{s_i}{2} + w_i - \left(\frac{s_{i+1}}{2} + w_{i+1}\right)}{\Delta x}$$

xo_{ij} is the increment of x_{c_1}:

$$xo_{ij} = x_{c_1} + \sum_{j=1} (j-1)\Delta x_s + \sum_{i=1} (i-1)\Delta x_s$$

Δx_s is the step size (increment); and x_{c_i} is the initial x coordinate of the elemental (Δx) section:

$$x_{c_i} = x_{c_1}, x_{c_1} + xo_{ij}, x_{c_1} + 2xo_{ij}, \cdots, x_{c_1} + \left(\frac{\frac{l_{cw}}{2}}{\Delta x} - 2\right) xo_{ij}.$$

The subscript i refers to elemental sections Δx and the subscript j refers to subsections of Δx:

$$i = 1, 2, \cdots, \left(\frac{\frac{l_{cw}}{2}}{\Delta x} - 1\right) \qquad j = 1, 2, \cdots, \left(\frac{\Delta x}{\Delta x_s}\right).$$

The equations for the second conductor can be written in terms of $y_{1_{ij}}$ and $y_{2_{ij}}$:

$$y_{p1_{ij}} = 2y_{c_1} - y_{1_{ij}} \tag{20}$$

$$y_{p2_{ij}} = 2y_{c_1} - y_{2_{ij}}. \tag{21}$$

Wiggling can now be introduced into (18) and (19). The wiggly section is shown in Fig. 4(c). The initial value of the wiggle depth is computed first:

$$A_{d_0} = \frac{1}{2} \sum_{i=1}^{m/2} d_i'. \tag{22}$$

The wiggling slope is given by

$$q_{w_i} = \frac{d_i'}{\Delta x}.$$

With wiggle, (18) becomes

$$y_{w1_{ij}} = \begin{cases} y_{1_{ij}} + A_{d_i} + (xq_i - xo_{ij}) q_{w_i}, \\ \qquad i = \left[1, \cdots, \frac{m}{2}\right], \left[(m+1), \cdots, \left(m + \frac{m}{2}\right)\right], \cdots \\ y_{1_{ij}} + A_{d_i} + (xo_{ij} - xm_i) q_{w_i}, \\ \qquad i = \left[\left(\frac{m}{2} + 1\right), \cdots, m\right], \\ \qquad \left[\left(m + \frac{m}{2} + 1\right), \cdots, (2m)\right], \cdots \end{cases} \tag{23}$$

where

$$A_{d_i} = \begin{cases} A_{d_0}, \quad i = 1, \cdots, \frac{m}{2} \\ 0.5[xq_i - xo_{(m/2)1}] q_{w_i}, \\ \qquad i = \left(\frac{m}{2} + 1\right), \cdots, \left(m + \frac{m}{2}\right) \\ 0.5[xq_i - xo_{(m+m/2)1}] q_{w_i}, \\ \qquad i = \left(m + \frac{m}{2} + 1\right), \cdots, \left(2m + \frac{m}{2}\right) \\ 0.5[xq_i - xo_{(2m+m/2)1}] q_{w_i}, \\ \qquad i = \left(2m + \frac{m}{2} + 1\right), \cdots, \left(3m + \frac{m}{2}\right) \\ \vdots \qquad \vdots \end{cases}$$

$$xq_i = \begin{cases} xo_{11}, & i = 1, \cdots, m \\ xo_{(m+1)1}, & i = (m+1), \cdots, 2m \\ xo_{(2m+1)1}, & i = (2m+1), \cdots, 3m \\ \vdots & \vdots \end{cases}$$

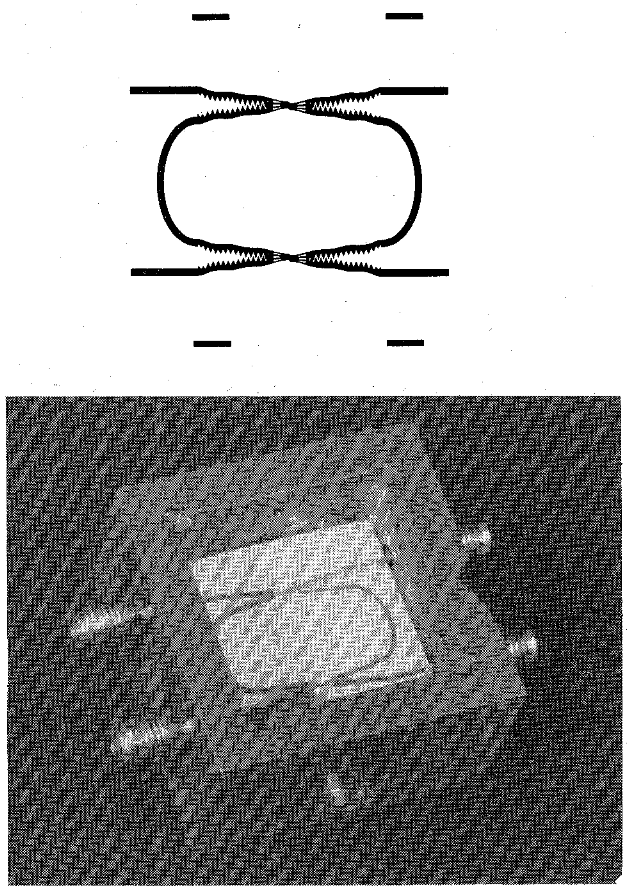

Fig. 5. Mask and photograph of the nonuniform directional coupler.

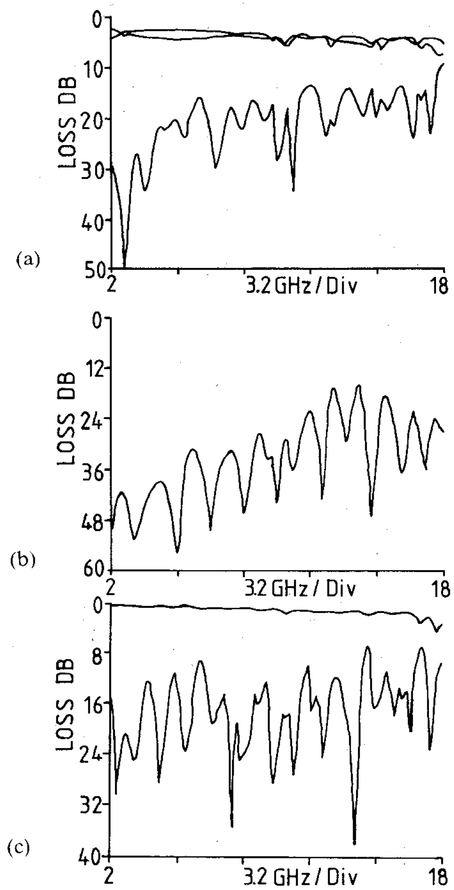

Fig. 6. Measured performance. (a) Coupled ports and return loss. (b) Isolation. (c) Measured isolated port with open-circuited coupled ports.

and

$$xm_i = \begin{cases} xo_{(m/2)1}, & i = 1, \cdots, \left(m + \frac{m}{2} - 1\right) \\ xo_{(m+m/2)1}, & i = \left(m + \frac{m}{2}\right), \cdots, \left(2m + \frac{m}{2} - 1\right) \\ xo_{(2m+m/2)1}, & i = \left(2m + \frac{m}{2}\right), \cdots, \left(3m + \frac{m}{2} - 1\right) \\ \vdots & \vdots \end{cases}$$

The quantity $y_{2_{ij}}$ is not affected by wiggling, i.e., $y_{w2_{ij}} = y_{2_{ij}}$. The same formulation is also valid for the second conductor. To generate the mask of the directional coupler, a step size of $\Delta x_s = 2.5\ \mu$m is taken.

D. Experimental Results

The designed coupler was built on $1 \times 1 \times 0.025$ in.^{3} alumina substrate. The mask and photograph of the coupler are given in Fig. 5. The coupler was measured with an HP8410 semiautomatic network analyzer and the performance is shown in Fig. 6. The measured coupled ports were found to be in balance within 1.7 dB in the 2–17 GHz band. The 0.025-mm-diameter gold bond wires used for crossovers and to connect the alternative fingers have undesirable effects on the overall coupler performance. A maximum number of three short lengths of bond wires were used.

The 3.5 mm OSM type launchers used for the transitions were not included in the calibration. These contribute to the coupler loss, especially above X-band frequencies.

V. Discussions

At present, a direct synthesis technique for the design of nonuniform directional couplers in inhomogeneous media is not available. The continuous physical parameters of nonuniform coupled lines have been synthesized by the use of cubic splines which are derived for $w(k)$, $s(k)$, and $d(k)$ from the static capacitances of uniform coupled lines. This method is found to provide satisfactory results. However, Getsinger's dispersion functions [20] for uniform coupled lines are not exact. There is an overestimation in the odd-mode dispersion function. In this paper no attempt has been made to modify his equations.

The main probable source of error arises when selecting the initial *uncoupled separation*, s_1. Theoretically, the uncoupled separation of two lines occurs at $s_1 = \infty$ with $f = 0$. Therefore, we should expect a drastic decrease in s_1 when a design center frequency of several gigahertz (in this paper 10 GHz) is selected. The computations confirmed this fact and s_1 is selected as 1760 μm. Generally, the coupling value at the selected s_1 should be added on $k(x)$ by defining $k(-l/2) = k_{s_1}(-l/2)$ instead of the zero coupling value which would be specified in the synthesis of $k(x)$.

The selection of step size for the determination of $k(x)$ is a critical point. If a large value of Δx ($\Delta x > 0.1$ mm) is selected, then the synthesized $k(x)$ would give smaller coupling values, which will cause larger errors at the center. This value of Δx should also match the value selected for the determination of wiggle depth. In this paper the value of Δx selected for the determination of $d(k)$ is 0.1 mm with the definition given in Fig. 2. For the synthesis of $k(x)$ this value is 0.05 mm with the proposed construction technique given in Fig. 4(c). Therefore these values provide effectively the same increase in the odd-mode length.

Nonuniform lines have a continuously varying slope. This will result in a slightly longer coupler length, thereby resulting in a shift of the design center frequency. This can be corrected by computing the slopes q_{1_i} and q_{2_i} and then computing the approximate inclined elemental length shown in Fig. 4(b). An average increase of 3 percent in the axial length is computed. To include this correction the step size for the construction should be made variable. Instead of this a compromise has been reached and the length of the center section is reduced by 0.3 mm and the outer sections each by 0.08 mm, resulting in an overall coupler length of 14.6 mm.

A coupler was built on alumina substrate and was repeatedly measured by bonding additional short lengths of gold bond wires. With two or less bond wires, higher ripples were measured in the coupler performance. However, with two bond wires the return loss measured was lower than -16 dB over the entire bandwidth of 2–18 GHz. The final measurements were made with a maximum number of three bond wires at the crossovers but the coupler center connection was left with two bond wires. For better performance the number of bond wires should be optimized for each different crossover by taking extreme care in locating the bond wires to minimize the discontinuity effects.

VI. Conclusions

A computer-aided design procedure is developed for nonuniform quadrature directional couplers in inhomogeneous media. Cubic splines of strip width, strip spacing, and wiggled depth as functions of coupling coefficient are computed using static capacitances of uniform coupled lines. These functions are then used as synthesis functions to evaluate the continuous physical parameters of nonuniform coupled lines by using the optimized $k(x)$.

A nonuniform interdigitated coupler is introduced to realize the tight coupling values. Manufacturing tolerances on wiggle depth are derived. These are found to be quite large and they must be included in the design.

A reduction in the overall coupler length of approximately 15 percent is achieved by wiggling. The improvement in isolation is excellent for the lower frequencies and about 10 dB for the higher frequencies when compared with a coupler without wiggling. The measured performance is satisfactory for many multioctave MIC applications. This coupler will be used in the design of a 2–18 GHz reflection-type analog phase shifter.

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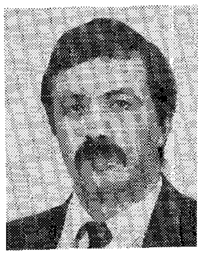

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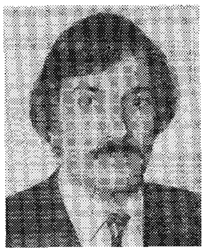

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