High Directivity CTL-Couplers and a New Technique for the Measurement of CTL-Coupler Parameters

STIG REHNMARK, MEMBER, IEEE

Abstract—**A very powerful method to measure the parameters of a one-section *C*oupled *T*ransmission *L*ine (CTL) coupler is presented. Three transmission measurements at the frequency of maximum coupling is sufficient to give the even- and odd-mode impedances (Z_e,Z_o) and the even- and odd-mode lengths (θ_e,θ_o). Explicit equations are presented for the necessary calculations.**

Data for some stripline couplers measured with the new method are presented. The data show a very significant length difference between the even and odd modes, although boards with the same dielectric constant (measured according to the MIL standard) were used. Improved dielectric-constant measurement techniques for thin boards have been developed. The presented methods give more relevant information of dielectric constant and Q value of the thin boards.

A new method for wide-band improvement of CTL-coupler directivity when $\theta_e \neq \theta_o$ has been developed. The theory is presented with all necessary equations and it covers both $\theta_e > \theta_o$ (microstrip) and $\theta_e < \theta_o$. The new method makes use of short compensating sections in the coupler to achieve a directivity pole at an arbitrary frequency. The wanted bandwidth determines the optimum location of the pole. Several examples with design data are given.

I. Introduction

A CTL-COUPLER is characterized by the even- and odd-mode impedances (Z_e,Z_o) and the even- and odd-mode lengths (θ_e,θ_o) as is shown in Fig. 1.

It is well known that a *C*oupled *T*ransmission *L*ine (CTL) coupler with unequal even- and odd-mode lengths suffers from low directivity. A length difference between the even and odd mode can be caused by:

a) different dielectric layers (for example, microstrip);
b) inhomogeneous dielectric (for example, glass fibers in Teflon);
c) rough Cu surface (for example, electrodeposited Cu on Teflon);
d) corner effects where the two coupled lines are launched;
e) different "paths" of the even and odd mode [1], [2];
f) meander-folding of coupled lines in homogeneous dielectric [2], [3].

Methods to improve the directivity of microstrip couplers (i.e., the even mode is longer than the odd mode) have been suggested by Podell [4], Buntschuh [5], and Rehnmark [3]. Little has been presented for the case where the even mode is shorter than the odd mode. The latter case is, however, very important since that is what we measure for "homogeneous"

Manuscript received May 5, 1977; revised July 18, 1977.
The author is with Anaren Microwave, Inc., Syracuse, NY 13205, on leave from the Division of Network Theory, Chalmers University, Göteborg, Sweden.

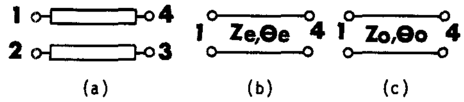

Fig. 1. The coupled transmission-line coupler. (a) Total circuit. (b) Even-mode circuit. (c) Odd-mode circuit.

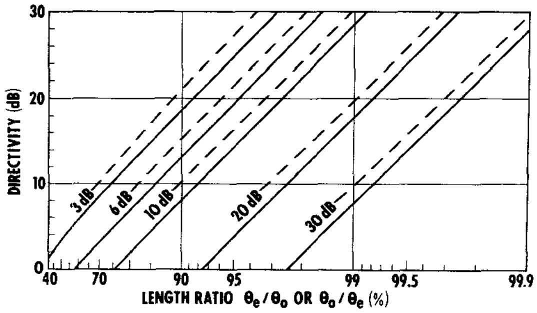

Fig. 2. Calculated minimum directivity over 2.3 : 1 bandwidth for single-section CTL-couplers with unequal even- and odd-mode lengths. ——— Conventional design $Z_e \cdot Z_o = 1$. - - - - - - - Optimum directivity design, $Z_e \cdot Z_o \neq 1$.

dielectric (commercially available glass-fiber reinforced Teflon) stripline couplers. The work presented here is a part of a research program at Anaren Microwave, Inc., with the following goals.

1) Develop a method to measure the even- and odd-mode impedances (Z_e,Z_o) and the even- and odd-mode lengths (θ_e,θ_o) of a single-section CTL-coupler.
2) Measure the length ratio of the two modes (θ_e/θ_o) as a function of frequency and coupling.
3) Determine the cause of the length difference.
4) Develop a method to achieve high-directivity couplers.

The main purpose of this paper is to present the results from Parts 1 and 4 above.

A theoretical analysis of single-section CTL couplers has been made in order to calculate the minimum directivity over a 2.3 : 1 bandwidth (octave bandwidth with some margin). The results of this analysis are shown in Fig. 2. The conventional coupler has an impedance level equal to $\sqrt{Z_e \cdot Z_o} = 1$, which will give a lower directivity at the high end of the band (solid curves). There exists an impedance, however, that will optimize the directivity over the band (dashed curves). The directivity improvement is about 2 dB when the optimum impedance level is used. See also Table II and Figs. 10 and 11 for additional data.

II. A Measurement Method of CTL-Coupler Parameters

The presented measurement method has been used to measure the parameters of numerous experimental couplers and then optimize the performance. The method requires three measurements at a well-specified frequency. The procedure is as follows.

1) Determine the frequency where the coupling is maximum.

2) Measure at that frequency, with the coupled port as reference:

a) DIR is the directivity, which is 20 log ($|S_{31}|/|S_{21}|$);

b) ADIR is the angle of directivity, which is $\underline{/S_{31}} - \underline{/S_{21}}$;

c) CREL is the relative coupling, which is 20 log ($|S_{41}|/|S_{21}|$).

3) DIR, ADIR, and CREL are input data in a computer program that gives Z_e, Z_o, θ_e, and θ_o.

S_{21}, S_{31}, and S_{41} are the scattering parameters of the coupler.

Explicit formulas for the calculation of Z_e, Z_o, θ_e, and θ_o have been found for the two special cases $Z_e \cdot Z_o = 1$ (ADIR = 0 or 180°) and $\theta_e = \theta_o$ (ADIR = ±90°), respectively. An approximate solution for the general case is found by using the projection of the directivity vector on the axis where ADIR = 0 and on the axis where ADIR = 90°. The equations are

$$\Delta\phi = \cos(\text{ADIR}) \cdot 10^{\text{DIR}/20} \tag{1}$$

$$\Delta Z = \sin(\text{ADIR}) \cdot 10^{\text{DIR}/20} \tag{2}$$

$$CR = 10^{\text{CREL}/20} \tag{3}$$

$$CA = (CR + \Delta Z)/(CR - \Delta Z) \tag{4}$$

$$CB = 2 \cdot (CA + 1)/CR \tag{5}$$

$$H = (1 + CB \cdot CB/4 - CA \cdot CA)/(CA \cdot CB) \tag{6}$$

$$Z_o = \sqrt{H \cdot H + 1} - H \tag{7}$$

$$Z_e = CB/2 + CA \cdot Z_o \tag{8}$$

$$\Delta\theta = -\tan^{-1}[(Z_e + 1/Z_e) \cdot \Delta\phi/(2 \cdot CR)] \tag{9}$$

$$\theta_e = 90 + \Delta\theta \tag{10}$$

$$\theta_o = 90 - \Delta\theta. \tag{11}$$

The approximate method gives small errors when $\Delta\theta$ and/or $(Z_e \cdot Z_o - 1)$ are small. For other cases, a computer optimizing program has been developed to minimize the error of the calculated parameters.

III. Some Results from Stripline CTL-Coupler Measurements

Fig. 3 shows the measured performance of a 3- and a 25-dB coupler compared to the theoretical performance with the measured Z_e, Z_o, θ_e, and θ_o as input data. Table I gives the parameters used. As is seen in the figure, the agreement is very good between measured performance and calculated performance using the measured Z_e, Z_o, θ_e, and θ_o.

All the parameters in Table I represent measurements of L-band stripline couplers. The dielectric boards are glass-fiber reinforced Teflon with a groundplane spacing of 65 mils, a centerboard thickness of 5 mils, and a dielectric constant (measured according to the MIL standard) of 2.6. The coupled lines are connected to 50-Ω lines by standard mitered right-angle bends. Fig. 4 shows some experimental 3-dB couplers in the frequency range 250 MHz–4 GHz.

It is shown in the table that the even- and odd-mode length difference is large for tight coupling. Curve a in Fig. 5 shows the ratio θ_e/θ_o versus coupling for the same set of couplers as in Table I. Curve b represents a set of couplers with a thicker centerboard (doubled) and twice the ground-

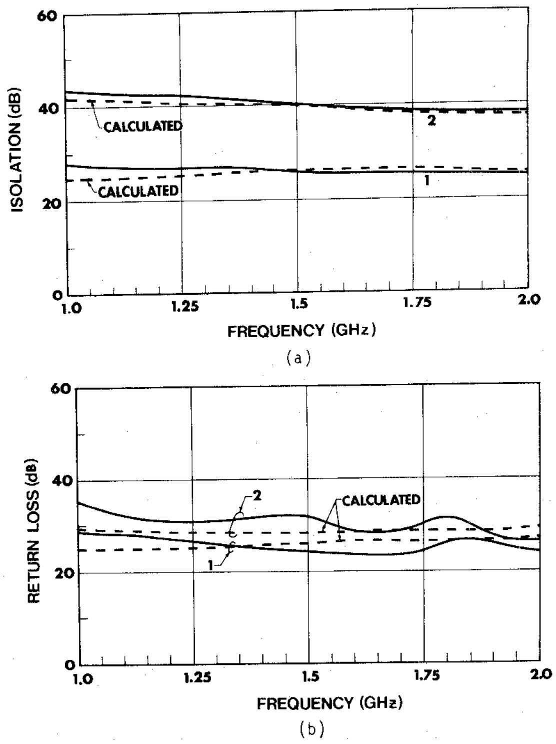

Fig. 3. Measured and calculated curves of L-band CTL-couplers. The parameters are found in Table I. (a) Isolation. (b) Return loss.

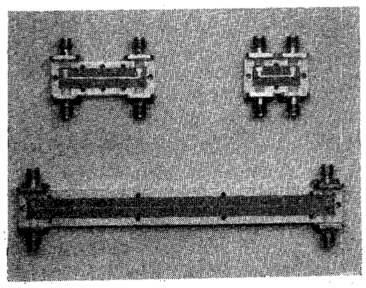

Fig. 4. Experimental stripline couplers, 250 MHz–4 GHz.

TABLE I
Parameters of Measured L-Band Stripline Couplers

Curve	DIR (dB)	ADIR (Degr)	CREL (dB)	θ_e (Degr)	θ_o (Degr)	θ_e/θ_o (%)	CPL* (dB)	IMP** (ohm)
1	-23.2	-38.2	-0.68	85.0	94.9	89.6	-2.66	0.939
-	-20.0	-38.0	2.5	85.6	94.1	91.0	-4.40	0.926
-	-21.0	-18.0	6.0	87.1	92.5	94.1	-6.96	0.970
-	-19.0	-4.5	13.8	88.6	91.2	97.1	-13.97	0.991
2	-14.8	-12.0	24.5	89.0	90.2	98.7	-24.48	0.962

*CPL = 20 log[(Ze-Zo)/(Ze+Zo)] **IMP = $\sqrt{Ze \cdot Zo}$

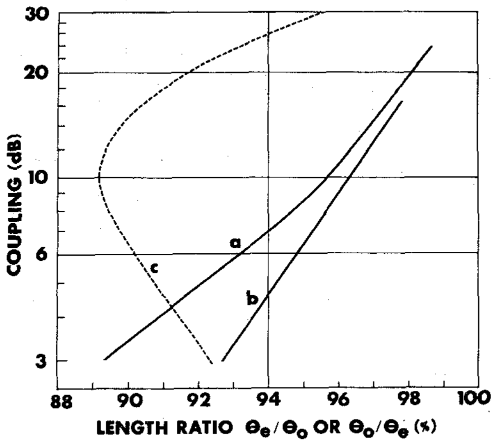

Fig. 5. Ratio of even- and odd-mode lengths of couplers. (a) Stripline: $\varepsilon = 2.6$, 5-mil centerboard, 65-mil groundplane spacing. (b) Stripline: $\varepsilon = 2.6$, 10-mil centerboard, 130-mil groundplane spacing. (c) Microstrip: $\varepsilon = 10$, theoretical calculation [5]. ——— $\theta_e < \theta_o$. - - - - - - - $\theta_e > \theta_o$.

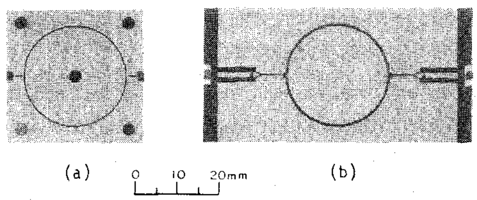

Fig. 6. Single- and coupled-loop resonators.

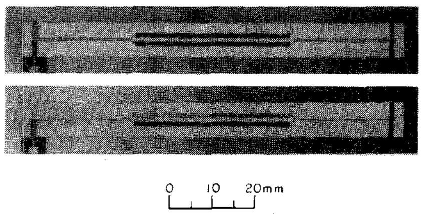

Fig. 7. Coupled-line resonators.

plane spacing. We see that the even- and odd-mode length difference is somewhat less for the thicker board, but still we are far from the optimum case. Both curves are plotted for L-band couplers. Only relatively small changes with frequency were observed, however, although a frequency range of more than a decade was covered.

To show how large the even- and odd-mode length difference is in stripline, a comparison was made with the microstrip case. Curve c in Fig. 5 shows the (calculated) even- to odd-mode length ratio for microstrip couplers on a substrate with a dielectric constant of 10. The data were found in [5]. Surprisingly enough, we find that the length difference between the even and odd modes is sometimes larger in "homogeneous" stripline than in microstrip with a high dielectric-constant substrate.

IV. Effective Dielectric-Constant Measurement of Thin Boards

Since our measurements show a large difference in length between the even and odd modes, we decided to make some dielectric-constant measurements. In particular, we wanted to measure the dielectric constant of the 5-mil centerboard. Stripline dielectric-constant measurement according to the MIL standard [6] is made with a line resonator. The line is 1.500 in long and a resonance around 10 GHz is used. The groundplane spacing is $\simeq 125$ mils, i.e., two $\frac{1}{16}$-in boards. Thinner boards are measured by stacking the boards to $\frac{1}{16}$-in thickness on each side of the strip.

The MIL-standard measurement may be good for characterizing unclad thin boards, but we find that it does not give adequate information for Cu-clad boards to be used in, for instance, a coupler. The same is true for the two fluid-cell method, a widely used low-frequency (1-MHz) dielectric-constant measurement method.

Fig. 6(a) shows a resonant loop. The loop was etched on one side of a 5-mil board and used with another 5-mil board in a stripline configuration. The groundplane spacing is then 10 mils (+Cu thickness). To eliminate air (due to the Cu thickness) and minimize clamping pressure sensitivity, we used a thin layer of Vaseline around the loop. Vaseline has a low dissipation factor and a dielectric constant of 2.16.

We find that the measured dielectric constant depends on how the copper is bonded to the dielectric. The same boards were measured with an electrodeposited copper loop etched out and with a brass loop. We find that the rough surface of the electrodeposited copper increases the measured dielectric constant up to 10 percent. No change with frequency was observed in the measured range of 1–18 GHz.

Obviously, the measured dielectric constant depends on the distance from the strip to ground; therefore, we wanted an even better way to characterize the thin board. We then developed the coupled-loop resonator shown in Fig. 6(b). Two loops are etched on each side of the thin board (complete overlap) and used with two thick boards in a complete stripline package. The linewidth and board thicknesses were the same as we wanted to use in a coupler; i.e., the loops and the coupler has the same cross section. The loops are excited in an even or odd mode, and we can measure the even- and odd-mode dielectric constant for the coupler in mind. The two odd-mode feed networks shown in Fig. 6(b) consist of baluns with extremely good phase tracking and amplitude balance of the two outputs [7].

With the same cross section as for the 3-dB coupler in Table I, the rough Cu surface causes an increase of the measured odd-mode dielectric constant of $\simeq 15$ percent. The even-mode dielectric constant is merely unaffected by Cu roughness. (Another unwanted effect caused by the Cu roughness is an increase of the odd-mode loss to several times the loss of the even mode.)

A similar dielectric-constant measurement technique has been developed for couplers with offset lines. Fig. 7 shows two coupled-line resonators. The baluns are of the same type as for the coupled-loop resonator, but are designed for a higher frequency ($\simeq 10$ GHz). Two slightly different baluns were used depending on whether the resonant lines are on the same level (upper circuit) or on each side of a thin board (lower circuit).

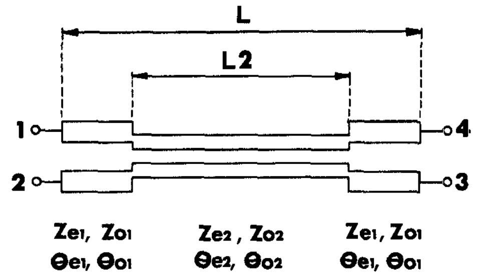

Fig. 8. The new coupler with compensating sections.

We find that for a 20-dB coupler, the Cu roughness is not as important as for a 3-dB coupler. Due to the separation of the coupled lines, however, a major part of the odd-mode field is parallel to the groundplanes and to the glass fibers. The high dielectric constant of glass makes the dielectric constant for the parallel field about 15 percent higher than for the perpendicular field. This results in a lengthening of the odd mode compared to the even mode.

V. Improving the Directivity of CTL-Couplers

The circuit used to improve the directivity of a coupler when $\theta_e \neq \theta_o$ is shown in Fig. 8. The circuit consists of a noncommensurate, symmetrical three-section coupler with a total length of $L \simeq \lambda o/4$.

We now suppose that

$$\frac{\theta_{e1}}{\theta_{o1}} = \frac{\theta_{e2}}{\theta_{o2}} = \frac{\theta_e}{\theta_o} \tag{12}$$

and then we design the circuit for infinite isolation at one (optional) frequency close to the center frequency of the device. The conditions for infinite isolation at the frequency fr (fr $= 1 \hat{=} L = \lambda o/4$) are

$$\frac{\dfrac{1+(t_{1e}t_{2e})^2}{t_{1e}t_{2e}} - R_e - \dfrac{1}{R_e}}{\dfrac{t_{1e}^2+t_{2e}^2}{t_{1e}t_{2e}} + R_e + \dfrac{1}{R_e}} = \frac{\dfrac{1+(t_{1o}t_{2o})^2}{t_{1o}t_{2o}} - R_o - \dfrac{1}{R_o}}{\dfrac{t_{1o}^2+t_{2o}^2}{t_{1o}t_{2o}} + R_o + \dfrac{1}{R_o}} \tag{13}$$

$$Z_{e2} \cdot Z_{o2} = \frac{1}{R_e R_o} \frac{(1 - t_{1o}t_{2o}/R_o)(t_{1e} + R_e t_{2e})}{(t_{1o} + t_{2o}/R_o)(1 - R_e t_{1e} t_{2e})} \tag{14}$$

where

$$R_e = Z_{e1}/Z_{e2} \tag{15}$$

$$R_o = Z_{o1}/Z_{o2} \tag{16}$$

$$t_{1e} = \tan(\text{fr} \cdot \theta_{e1}) \tag{17}$$

$$t_{2e} = \tan(\text{fr} \cdot \theta_{e2}/2) \tag{18}$$

$$t_{1o} = \tan(\text{fr} \cdot \theta_{o1}) \tag{19}$$

$$t_{2o} = \tan(\text{fr} \cdot \theta_{o2}/2) \tag{20}$$

$$\theta_e = 90 + \Delta\theta = 2\theta_{e1} + \theta_{e2} \tag{21}$$

$$\theta_o = 90 - \Delta\theta = 2\theta_{o1} + \theta_{o2} \tag{22}$$

$$\frac{L2}{L} = \frac{\theta_{e2}}{\theta_e} = \frac{\theta_{o2}}{\theta_o}. \tag{23}$$

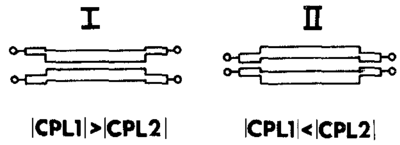

Fig. 9. Different realizations of the compensated coupler.

By a straightforward calculation, we can eliminate R_e, R_o, Z_{e1}, Z_{o1}, Z_{e2}, and Z_{o2} in (13) and (14) and use

$$\text{CPL1} = 20 \log [(Z_{e1} - Z_{o1})/(Z_{e1} + Z_{o1})] \tag{24}$$

$$\text{CPL2} = 20 \log [(Z_{e2} - Z_{o2})/(Z_{e2} + Z_{o2})] \tag{25}$$

$$\text{IMP1} = \sqrt{Z_{e1} \cdot Z_{o1}} \tag{26}$$

$$\text{IMP2} = \sqrt{Z_{e2} \cdot Z_{o2}}. \tag{27}$$

We observe that we have four independent parameters: $L2/L$, fr, CPL1, and CPL2 is a good choice. Equations (13) and (14) then give IMP1 and IMP2. As shown in Fig. 9, there are two different realizations depending on whether the outer sections are more tightly or loosely coupled than the center section of the coupler.

A useful relationship between the two cases $\theta_e > \theta_o$ and $\theta_e < \theta_o$ has been found. It has been shown that the same performance (except $\underline{/S_{11}}$ and $\underline{/S_{31}}$) is achieved if

$$\frac{\theta_o}{\theta_e}(\theta_e > \theta_o) = \frac{\theta_e}{\theta_o}(\theta_e < \theta_o) \tag{28}$$

$$\text{CPL1}\ (\theta_e > \theta_o) = \text{CPL1}\ (\theta_e < \theta_o) \tag{29}$$

$$\text{CPL2}\ (\theta_e > \theta_o) = \text{CPL2}\ (\theta_e < \theta_o) \tag{30}$$

$$\text{IMP1}\ (\theta_e > \theta_o) = 1/\text{IMP1}\ (\theta_e < \theta_o) \tag{31}$$

$$\text{IMP2}\ (\theta_e > \theta_o) = 1/\text{IMP2}\ (\theta_e < \theta_o). \tag{32}$$

To get an idea of the usefulness of the compensating method, a number of calculations have been made. Theoretical data for several couplers are given in Table II to give the reader a chance to draw his own conclusions.

Some theoretical curves for 3- and 20-dB couplers are shown in Figs. 10 and 11, respectively; the corresponding parameters are given in Table II. The table shows the case of $\theta_e < \theta_o$, as well as the case of $\theta_e > \theta_o$, since the same curves apply to both cases. The ratio $L2/L$ gives the length of the center section of the coupler compared to its total length. $L/(0.25\lambda_o)$ shows the total length of the coupler at the frequency of maximum coupling. $0.25\lambda_o$ corresponds to the frequency where the mean value of the total even- and odd-mode lengths equals 90°. The minimum return loss and directivity have been calculated for a 2.3 : 1 bandwidth (octave bandwidth with margin). All the couplers in Table II except the single-section couplers with IMP2 = 1 have been optimized so the directivity is the same at the two edges of the band. For the compensated couplers, this was done by varying the location of the directivity pole (parameter fr).

When we compare the coupling of a compensated coupler to that of a perfect coupler (over an octave), we see that the difference is generally less than a few hundredths of a decibel.

TABLE II

DESIGN DATA FOR COMPENSATED AND UNCOMPENSATED COUPLERS WITH UNEQUAL EVEN- AND ODD-MODE LENGTHS—DIRECTIVITY AND RETURN LOSS ARE CALCULATED FOR A 2.3 : 1 BANDWIDTH

Curve	Type of Circuit	Center Freq. Coupling (dB)	Θ_e/Θ_o or Θ_o/Θ_e (%)	$\Theta_e < \Theta_o$ IMP1 (ohm)	$\Theta_e < \Theta_o$ IMP2 (ohm)	$\Theta_e > \Theta_o$ IMP1 (ohm)	$\Theta_e > \Theta_o$ IMP2 (ohm)	CPL1 (dB)	CPL2 (dB)	$\frac{L2}{L}$	$\frac{L}{0.25\lambda o}$	Min. Ret. Loss (dB)	Min. Directivity (dB)
A		-2.73	90	---	1.000	---	1.000	---	-2.70	1.00	0.99	-23.1	-18.6
B		-2.70	90	---	0.939	---	1.065	---	-2.66	1.00	1.00	-24.5	-20.9
-	I	-2.70	90	0.459	0.949	2.179	1.054	-10.00	-2.63	0.90	1.06	-23.8	-20.9
C	I	-2.70	90	0.593	0.955	1.686	1.047	-30.00	-2.60	0.90	1.10	-25.5	-22.7
-	II	-2.70	90	1.200	0.520	0.833	1.923	-2.16	-7.00	0.10	0.90	-29.3	-26.5
D	II	-2.70	90	1.118	0.705	0.894	1.418	-1.88	-20.00	0.10	0.86	-34.6	-31.9
-		-5.57	93	---	1.000	---	1.000	---	-5.55	1.00	1.00	-28.1	-16.5
-		-5.55	93	---	0.928	---	1.078	---	-5.50	1.00	1.00	-23.8	-18.5
-	I	-5.55	93	0.307	0.933	3.257	1.072	-10.00	-5.39	0.90	1.01	-18.8	-16.5
-	I	-5.55	93	0.544	0.954	1.838	1.048	-30.00	-5.49	0.90	1.10	-23.4	-21.2
-	II	-5.55	93	1.138	0.920	0.879	1.087	-2.89	-10.00	0.40	0.81	-33.9	-32.2
-	II	-5.55	93	1.087	0.915	0.920	1.093	-2.63	-20.00	0.30	0.76	-38.1	-36.7
-		-9.44	96	---	1.000	---	1.000	---	-9.43	1.00	1.00	-36.6	-16.4
-		-9.43	96	---	0.929	---	1.076	---	-9.38	1.00	1.00	-23.5	-18.3
-	I	-9.43	96	0.469	0.954	2.132	1.048	-20.00	-9.33	0.90	1.06	-21.9	-19.9
-	I	-9.43	96	0.564	0.958	1.773	1.044	-40.00	-9.37	0.90	1.10	-23.6	-21.6
-	II	-9.43	96	1.312	0.995	0.762	1.005	-2.20	-10.00	0.90	0.84	-36.4	-34.7
-	II	-9.43	96	1.088	0.974	0.919	1.027	-3.34	-15.00	0.60	0.73	-40.6	-39.9
E		-19.38	98	---	1.000	---	1.000	---	-19.38	1.00	1.00	-52.5	-11.9
F		-19.38	98	---	0.885	---	1.130	---	-19.25	1.00	0.99	-18.4	-13.8
G	I	-19.38	98	0.390	0.929	2.564	1.076	-40.00	-19.21	0.90	1.09	-18.5	-16.7
H	II	-19.38	98	1.239	0.994	0.807	1.006	-6.02	-21.00	0.90	0.77	-40.5	-39.5
-	II	-19.38	98	1.107	0.993	0.903	1.007	-2.52	-25.00	0.90	0.65	-48.9	-48.9
-		-29.37	99	---	1.000	---	1.000	---	-29.37	1.00	1.00	-68.5	-7.9
-		-29.37	99	---	0.826	---	1.211	---	-29.07	1.00	0.97	-14.4	-10.1
-	II	-29.37	99	1.281	0.992	0.781	1.008	-13.04	-32.00	0.90	0.73	-40.7	-40.1
-	II	-29.37	99	1.169	0.993	0.855	1.007	-9.81	-35.00	0.90	0.66	-46.5	-46.5

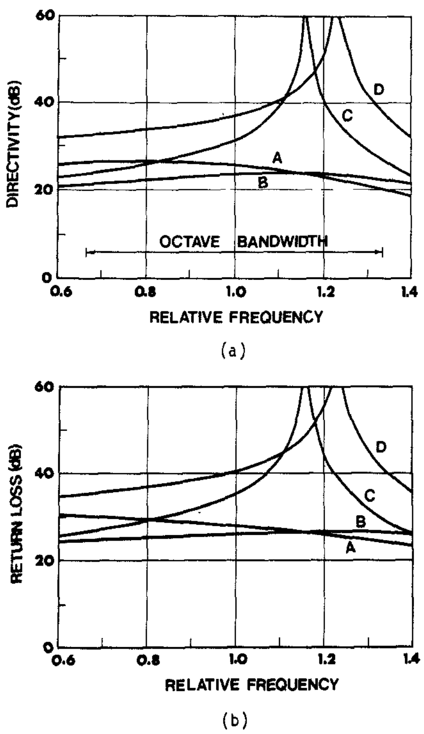

Fig. 10. Theoretical curves of couplers with a center-frequency coupling of 2.7 dB. The parameters are found in Table II. (a) Directivity. (b) Return loss.

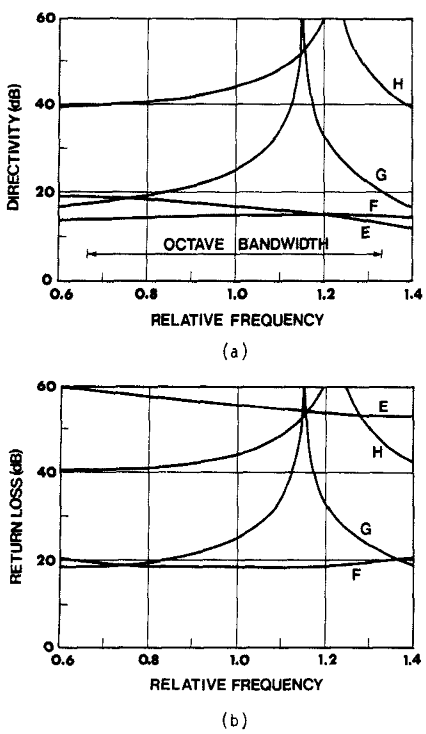

Fig. 11. Theoretical curves of couplers with a center-frequency coupling of 19.4 dB. The parameters are found in Table II. (a) Directivity. (b) Return loss.

The coupling maximum of a compensated coupler is moved in frequency for circuit I to a higher frequency (lengthening effect) and for circuit II to a lower frequency (shortening effect).

We find (Table II) that the widest bandwidth for circuit I is obtained when the outer sections are as short as possible and have low coupling. The limiting factor is that IMP1 goes very low ($\theta_e < \theta_o$) or high ($\theta_e > \theta_o$). For stripline couplers

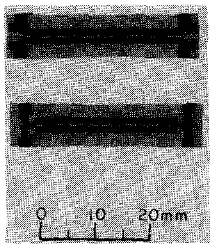

Fig. 12. Experimental *L*-band stripline couplers with compensating sections.

($\theta_e < \theta_o$) the outer sections take the form of tabs and have been used for years at Anaren Microwave, Inc. (and some other industries), but no quantitative theory has been presented. A comparison between the new theory and experimental circuits shows good agreement.

The widest bandwidth for circuit II is achieved when the outer sections are short and the center section has low coupling. The limiting factor is the coupling in the outer sections. The directivity improvement over a 2.3 : 1 bandwidth is generally better than for circuit I. Circuit II is particularly effective when the overall coupling is 10 dB or less.

To verify the presented theory, several experimental circuits were tested. Typical circuits are shown in Fig. 12. The figure shows two 20-dB *L*-band couplers. The type-I circuit (upper in the figure) is physically longer since the length L includes the tabs. The shown type-I circuit is centered at 1.5 GHz and the type-II circuit at 1.2 GHz (a lower frequency due to the shortening effect).

VI. Conclusion

A new method to measure the parameters of CTL-couplers has been presented, including explicit formulas for the necessary calculations. The method has been very useful in practice for the correction of couplers with $Z_e \neq 1/Z_o$ and/or $\theta_e \neq \theta_o$.

New techniques to measure the effective dielectric constant of thin boards were discussed. We feel that two measurements are needed to characterize the thin boards. Already established methods can be used to measure the dielectric constant of the boards, not including the effect of the rough Cu surface. Another measurement, for instance, with the coupled loop, is then made to get the effective dielectric constant, including the effect of the rough Cu surface.

A new circuit has been developed for improvement of the directivity of CTL couplers with different even- and odd-mode lengths. Explicit formulas were given for the design of couplers with a directivity pole at an arbitrary frequency. The presented curves show that a large improvement can be achieved over a wide bandwidth. The theory has been verified by several experimental couplers.

Acknowledgment

The author wishes to thank C. W. Gerst, Jr., Executive Vice-President at Anaren Microwave, Inc., for many discussions during this work and for permission to publish the results.

References

[1] R. Lagerlöf and S. Rehnmark, "VHF—Antenna feeder power divider," *Microwave J.* (Euro-Global Ed., July 1975).

[2] S. Rehnmark, "Theory and application of microwave couplers, phase shifters, and power dividers," Ph.D. thesis, School Elec. Eng., Chalmers Univ. Technol., Göteborg, Sweden, Tech. Rep. 62, Apr. 1976 (Paper D, pp. 6–8).

[3] ——, "Meander-folded coupled lines," *IEEE Trans. Microwave Theory Tech.*, to be published.

[4] A. Podell, "A high directivity coupler technique," in *Proc. G-MTT 1970 Int. Microwave Symp.* (May 1970), pp. 33–36.

[5] C. Buntschuh, "Octave-bandwidth, high directivity microstrip coupler," RADC-TR-73-396, Contract F30602-72-C-0282, AD 777320, Jan. 1974.

[6] M. Olyphant, Jr., and J. Ball, "Strip-line methods for dielectric measurements at microwave frequencies," *IEEE Trans. Elec. Insul.*, vol. EI-5, pp. 26–32, Mar. 1970.

[7] G. Laughlin, "A new impedance-matched wide-band balun and magic tee," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-24, pp. 135–141, Mar. 1976.