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Broadband, High-Performance Couplers with Dielectric Overlays for Microwave Integrated-Circuit Applications

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A systematic design approach is used to develop a class of high-performance, broadband, directional couplers for microwave integrated-circuit application. The couplers are characterized by two asymmetric quarter-wavelength coupling sections covered by dielectric overlays. All design parameters of these couplers, except the overlay thickness, are determined by computer analysis. This approach, which minimizes the empirical operations and improves the predictability and repeatability, results in a coupler design suitable for integrated systems production.

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20. Abstract (Continued)

The design, fabrication, and evaluation of 6-, 10-, and 20-dB directional couplers is presented. The measured and predicted performance characteristics of these couplers compare well and demonstrate the use of this systematic coupler-design approach. Sufficient design detail and discussion is included to permit reproduction of these dielectric-overlay couplers.

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BROADBAND, HIGH-PERFORMANCE COUPLERS WITH DIELECTRIC OVERLAYS FOR MICROWAVE INTEGRATED-CIRCUIT APPLICATIONS

OBJECTIVES

The object of this effort was to develop a class of high-performance, broadband, directional couplers from a systematic design approach that could be used in the production of microwave integrated-circuit (MIC) systems. Thus the coupler design technique stressed predictability and repeatability with a minimum of effort.

Three directional couplers were to be made with nominal coupling values of 6-, 10-, and 20-dB. These couplers represent respectively values of tight, and intermediate loose, coupling in common use. A set of high-performance electrical specifications was drawn up for each microstrip coupler (Table 1) using the performance achievable in its corresponding stripline counterpart as a guideline. In addition, it was also desired that these components exhibit minimal size and be fabricated by standard production techniques. Success in this type of investigation usually depends on the degree in which these couplers can be modeled for computer analysis. In the following section the choice of the type of coupler is made and the formulation of the design approach is described.

Table 1
Design Objectives* (Frequency Bandwidth: 2.5 — 8.5 GHz)

Coupler	Coupling (dB)	Worst VSWR	Directivity (dB)	Max. Loss† (dB)
6 dB	6 ± 0.75	1.3	15	2.3
10 dB	10 ± 0.75	1.3	15	1.2
20 dB	20 ± 0.75	1.3	15	0.5

*The values in this table include the effects of the terminations, connectors and VSWR's.
†Including the coupled signal.

BASIC COUPLER TYPES

In general, there is a variety of coupler types available that can be used for the same application. It becomes a question of compromise when one type is selected over another. One serious problem encountered in programs for the development of broadband MIC couplers is the difficulty in maintaining good directivity over the band. Degradation of directivity occurs when the even- and odd-mode phase velocities are unequal.

Note: Manuscript submitted February 11, 1975.

Two rather successful techniques used to control this problem are the wiggly-line [1] and dielectric-overlay approaches. For tight- and intermediate-coupling values, the wiggly line is an appealing technique since it can be incorporated into the lithography. Unfortunately, complete information for designing wiggly-line couplers is not currently available in the open literature. Furthermore, for loose coupling this approach becomes less effective and is inadequate for coupling values less than -17 dB. This is not true for the dielectric-overlay approach, which is effective for all values of coupling. It was mainly on this basis that edge-coupled microstrip lines with dielectric overlays were chosen as the basic configuration. Broadside-coupled lines were not considered because of the difficulty of interfacing them into MIC systems.

A single quarter-wavelength-section coupler will provide reasonable coupling performance for a bandwidth less than 2:1, but additional coupling sections are required for greater bandwidths. Calculations showed that the desired bandwidth requirement could be satisfied by a two-section asymmetric coupler. Had phase quadrature outputs been needed, it would have been necessary to go to a three-section symmetric coupler. Each coupling section is completely covered with a dielectric overlay whose dimensions are established by the coupled transmission lines. This type of coupler is readily fabricated in a microstrip format and has a geometry suitable for computer analysis. A detailed description of the design approach and development of the 6-, 10-, and 20-dB directional couplers follows.

DESIGN APPROACH

The 6-, 10-, and 20-dB microstrip couplers were fabricated on 25-mil-thick alumina substrates having a dielectric constant $K = 10$. Similar alumina substrates were cut up to provide the dielectric overlays which were fastened to the coupler with stycast epoxy ($K \approx 10$). A typical overlay coupler is shown in Fig. 1.

Each coupler had an asymmetric pattern using two quarter-wavelength (at midband frequency) coupling sections connected in cascade. One need bear in mind, however, that this approach is equally applicable to both asymmetric and symmetric directional couplers.

Initial coupling values for each section were taken from Levy's Tables [2], and the length of each section was determined from previous in-house work [3]. Coupling performance curves were then calculated (Appendix B) for these values of section coupling and length. Adjustment of these parameter values might be necessary to obtain the desired coupling performance over the band. Having done this, the length and lossless coupling value of each section are resolved, and only the dissipative loss of the device must be accounted for. In this case, for each coupler described a loss factor of 0.5 dB proved to be adequate. This loss estimate was based on previous coupler investigations, supplemented by open-literature information on isolated microstrip losses [4].

At this point the design objectives, adjusted for the loss expectations, furnish sufficient information to use a computer-program analysis which will determine the electrical characteristics for a given cross-section geometry of coupled microstrip transmission lines

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covered with a dielectric overlay. Program MICDOC [5] was developed for this purpose using a method of moments analysis implemented for digital computers. Figure 2a shows the input parameters which must be supplied to MICDOC. For a quarter-wavelength-long section characterized by such a set of parameters, MICDOC computes values for: the midband coupling, the characteristic impedance of the coupled lines, the even- and odd-mode impedances, the even- and odd-mode phase velocities, and the average phase velocity. The question of fabrication feasibility is clearly resolved by this computer-aided design approach. For a two-section coupler, Figs. 2b and 2c illustrate respectively the positioned dielectric overlays on the circuit pattern and the geometry of the inter-section transition.

When the design objectives have been theoretically satisfied, a directional coupler can be fabricated and evaluated. For the first model couplers, performance tests will usually show the coupling and match to be in good agreement with the design values, but the isolation will probably be very poor. This indicates that the even- and odd-mode phase velocities differ. This difference can be minimized by appropriately changing the thickness T of the dielectric overlay. Unfortunately, as T is adjusted to give optimum isolation, the match and coupling will also change, but to a lesser degree. If the change in T is too drastic, a new coupler geometry (with the new value of T) must be calculated by MICDOC to restore the proper impedance and coupling values. Empirical optimization of the directivity is obtained iteratively by repeating this operation until the desired performance characteristics are achieved. In practice, two or three rounds of this procedure are usually sufficient.

Furthermore, the test and evaluation of the coupler may indicate that the electrical lengths of the coupling section need adjusting. The exact value of this parameter is difficult to specify a priori because it is affected by the section coupling level and the intersection transition region. Errors in electrical length are manifested by a "tilting" or asymmetry of the coupling curve about the midband frequency (Appendix C).

At this point in the development method, regardless of the number of design and fabrication iterations, if the directional coupler exhibits satisfactory electrical performance characteristics, it will be referred to as a "systematic" coupler. This implies that the device has been developed in a format suitable for integrated systems. Every parameter is specified, and repeatability in production has been reduced to quality-control effectiveness. The systematic coupler is the prime objective of this design technique, but another option does exist. In the pragmatic case, where the only concern is to fulfill a specified need, a systematic coupler which does not quite meet specifications can frequently be "tuned" empirically to achieve the specified performance. This type of coupler generally sacrifices repeatability, since its performance must be monitored during the tuning operation. Unlike the systematic coupler which has prescribed dielectric overlays positioned solely by the coupler-pattern geometry, the tuned coupler is likely to have partial overlays (overlays with either length or width differing from those prescribed) located in disoriented positions relative to the circuit pattern.

During the development work, it was observed that the overlay thicknesses on the various sections of multiple couplers are interdependent. This suggests that an option exists to work on either individual coupling sections or the whole multisection device. Nevertheless, there are times when it is more expedient and economic to empirically tune a systematic coupler section by section. Some examples are provided in the next section, which compares the performance characteristics of a systematic coupler and a tuned coupler having the same coupling value. Figure 3 capsulizes the design procedure just described and used to develop all the hardware reported on in this study.

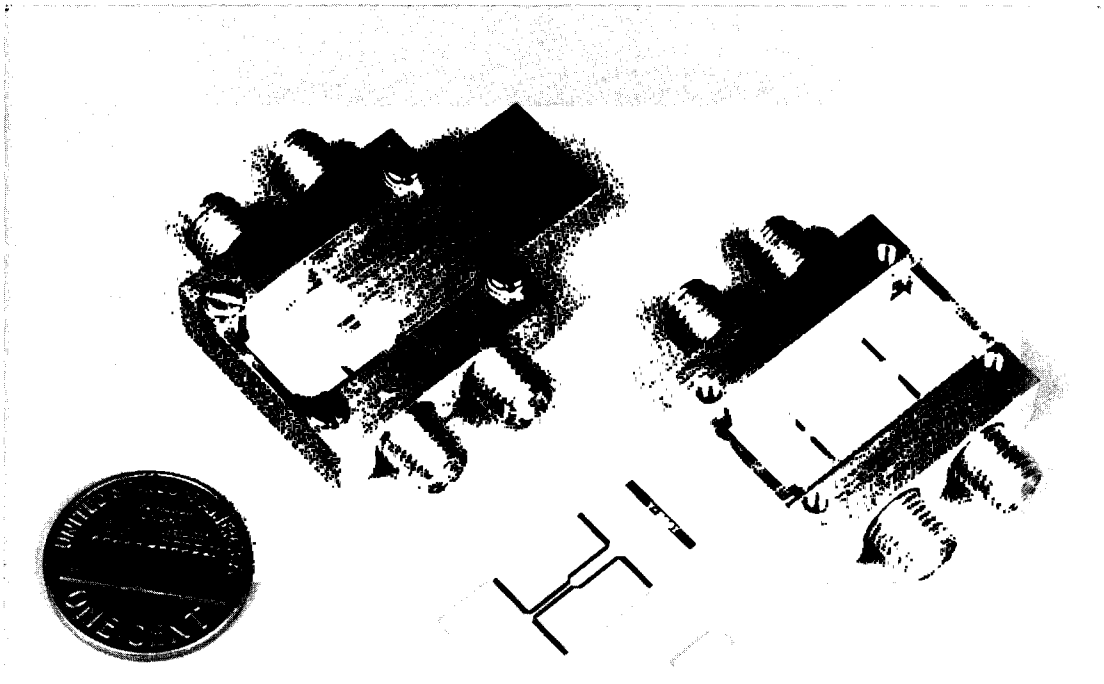

Fig. 1 — Two-section asymmetric broadband MIC directional coupler with dielectric overlays

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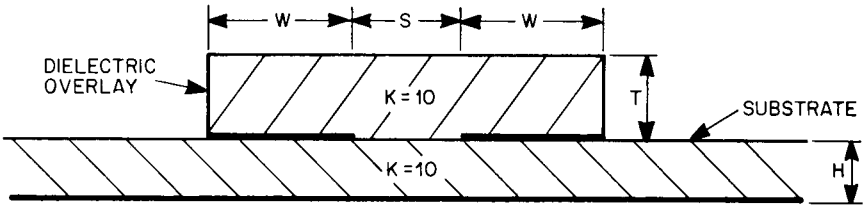
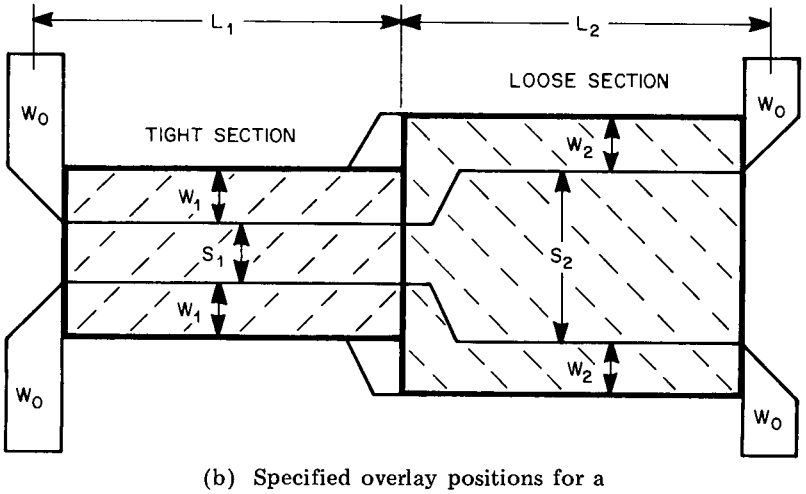
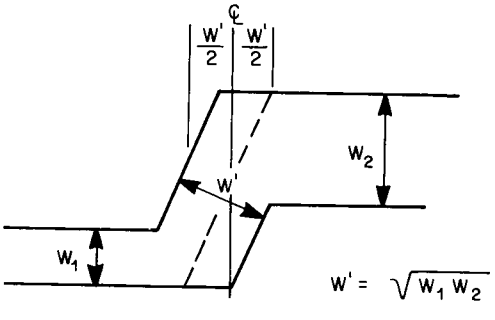


(a) Cross-section parameters of a coupling section used in computer program MICDOC



(b) Specified overlay positions for a two-section coupler



(c) Intersection-transition design

Fig. 2 — Dielectric-overlay coupler

1. SELECT THE LENGTH AND LOSSLESS COUPLING VALUES FOR EACH COUPLING SECTION.

2. CALCULATE THE COUPLING PERFORMANCE CURVE.

3. ADJUST THE COUPLING VALUES FOR THE DISSIPATION LOSS.

4. ASSUME A CROSS-SECTIONAL GEOMETRY FOR EACH COUPLING SECTION.

5. COMPUTER PROGRAM MICDOC CALCULATES THE SECTIONAL IMPEDANCE AND COUPLING VALUES.

6. FABRICATE, TEST, AND EVALUATE THE COUPLER.

7. EMPIRICALLY OPTIMIZE THE DIELECTRIC-OVERLAY THICKNESS FOR OPTIMUM DIRECTIVITY.

(SYSTEMATIC COUPLER)

OPTION:

8. TUNE THE SYSTEMATIC COUPLER TO MEET SPECIFICATIONS.

(TUNED COUPLER)

Fig. 3 — Overlay-coupler design approach

COUPLER PERFORMANCE

Introductory Considerations

This section contains the characteristic-performance results and the design-parameter values for the 6-, 10-, and 20-dB couplers. These couplers, although having different coupling values, have much in common with regard to the developmental considerations, and for this reason the 10 dB directional coupler will be singled out as representative of the class of microstrip couplers with dielectric overlays.

When the design objectives were formulated, the intention was to design and develop high-performance broadband MIC couplers in a frequency band of practical interest. The frequency range selected was 2.5 — 8.5 GHz. Each coupler used two asymmetric, cascaded, quarter-wavelength (at midband) sections because the bandwidth could be covered with only two sections and because phase-quadrature output signals were not required. The coupler patterns were etched on 25-mil-thick alumina substrates with $K \approx 10$ and used dielectric overlays of the same material.

A detailed description of the design approach will now be given using the 10 dB coupler as an example. However, with an effort to maintain a concise description of the development program some of the "general interest" design information is referred to the Appendices.

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10 dB Coupler

First, the lossless coupling values for the two coupling sections were determined from Levy's tables for a 4:1 bandwidth and a 0.75 dB coupling ripple. These coupling values were 7.2 dB and 15.7 dB for the tight- and loose-coupling sections respectively. Using these coupling values and assuming 0.5 dB dissipation loss for the device, calculations were made to determine the coupling performance over the band (Appendix B). It was found that for a tight section of length 0.219 in. and coupling value 6.9 dB, together with a loose section of length 0.219 in. and coupling value 16.0 dB, the coupling curve over the band is 9.50 ± 0.55 dB. Figure 4 shows this coupling curve with the loss factor taken into account. This performance curve, 10.00 ± 0.55 dB, was then the design objective.

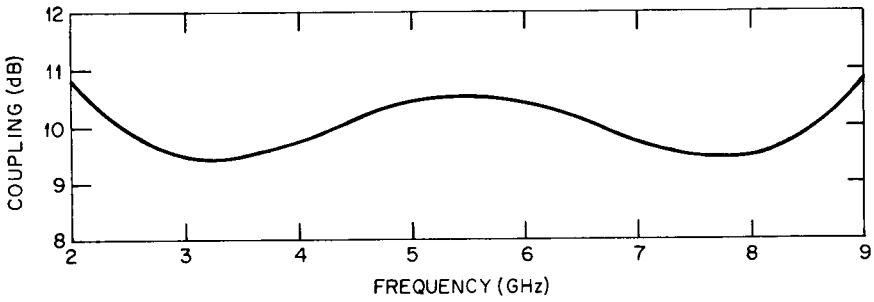

Fig. 4 — Target coupling performance for the 10 dB coupler with 0.5 dB loss compensation. C_1 = 6.9 dB, C_2 = 16.0 dB, $\ell_1 = \ell_2$ = 0.219 in.

Having established the quarter-wavelength-section midband coupling values, the only design parameters remaining to be specified, before using computer program MICDOC, are the characteristic impedance of each section and the thickness of the dielectric overlay on the coupled lines. In this work all sectional impedances were 50 ohms. Normally, on the very first coupler model the overlay thickness T is taken as some convenient substrate thickness. Table 2 contains design information and geometry parameters required by MICDOC for specific 6- and 20-dB couplers and an iteration sequence of 10 dB couplers. The performance characteristics for these four coupler models are shown in Figs. 5 — 8. The first 10 dB coupler model (Fig. 5) is interesting in that it behaves just as expected — rather decent performance in all respects except the directivity. After the first coupler model is evaluated, the next value of T (overlay thickness) is determined by experimental evidence rather than by convenience. Note how the value of T changes from 25 mils to 3 mils for the second-generation coupler (Fig. 6). The second coupler model exhibits significant performance improvement over the first model and begins to resemble the desired design objectives. An attempt was made to tune this systematic coupler by using partial overlays and pushing them about the circuit while monitoring the coupler performance. The results of this procedure appear in Fig. 7, where it is seen that some improvement in the performance had been gained. Finally, a third iteration of the design technique produced a systematic coupler with performance characteristics as shown in Fig. 8. These data compare favorably with the desired coupling curve of Fig. 4.

Table 2
Coupler Design Information and Geometry Parameters

Coupler Model	Coupling Section	Coupling (dB)	Z_0 (ohms)	L (mils)	H (mils)	W (mils)	S (mils)	T (mils)	Measured-Performance-Curve Figure
6 dB (Tuned)	Tight	3.49	50.0	200.0	25	8.5	1.4	10.0*	10
First Model	Loose	12.9	50.0	200.0	25	19.8	18.6	5.0*	
6 dB (Systematic)	Tight	3.48	50.0	200.0	25	8.75	1.2	7.0	11
Second Model	Loose	12.9	50.0	200.0	25	19.0	21.3	10.0	
10 dB (Systematic)	Tight	6.90	50.0	200.0	25	13.9	3.8	25.0	5
First Model	Loose	16.0	50.0	200.0	25	15.9	39.4	10.0	
10 dB (Systematic)	Tight	7.00	50.0	200.0	25	15.7	5.2	3.0	6
Second Model	Loose	16.0	50.0	200.0	25	20.0	30.4	10.0	
10 dB (Tuned)	Tight	7.00	50.0	200.0	25	15.7	5.2	3.5*	7
Second Model	Loose	16.0	50.0	200.0	25	20.0	30.4	10.0*	
10 dB (Systematic)	Tight	7.00	49.9	200.0	25	15.5	5.8	5.0	8
Third Model	Loose	16.0	49.9	200.0	25	19.0	32.3	14.0	
20 dB (Systematic)	Tight	16.9	50.0	200.0	25	18.8	39.8	25.0	13
Second Model	Loose	27.1	50.0	200.0	25	18.8	76.5	15.0	

*Indicates partial overlays

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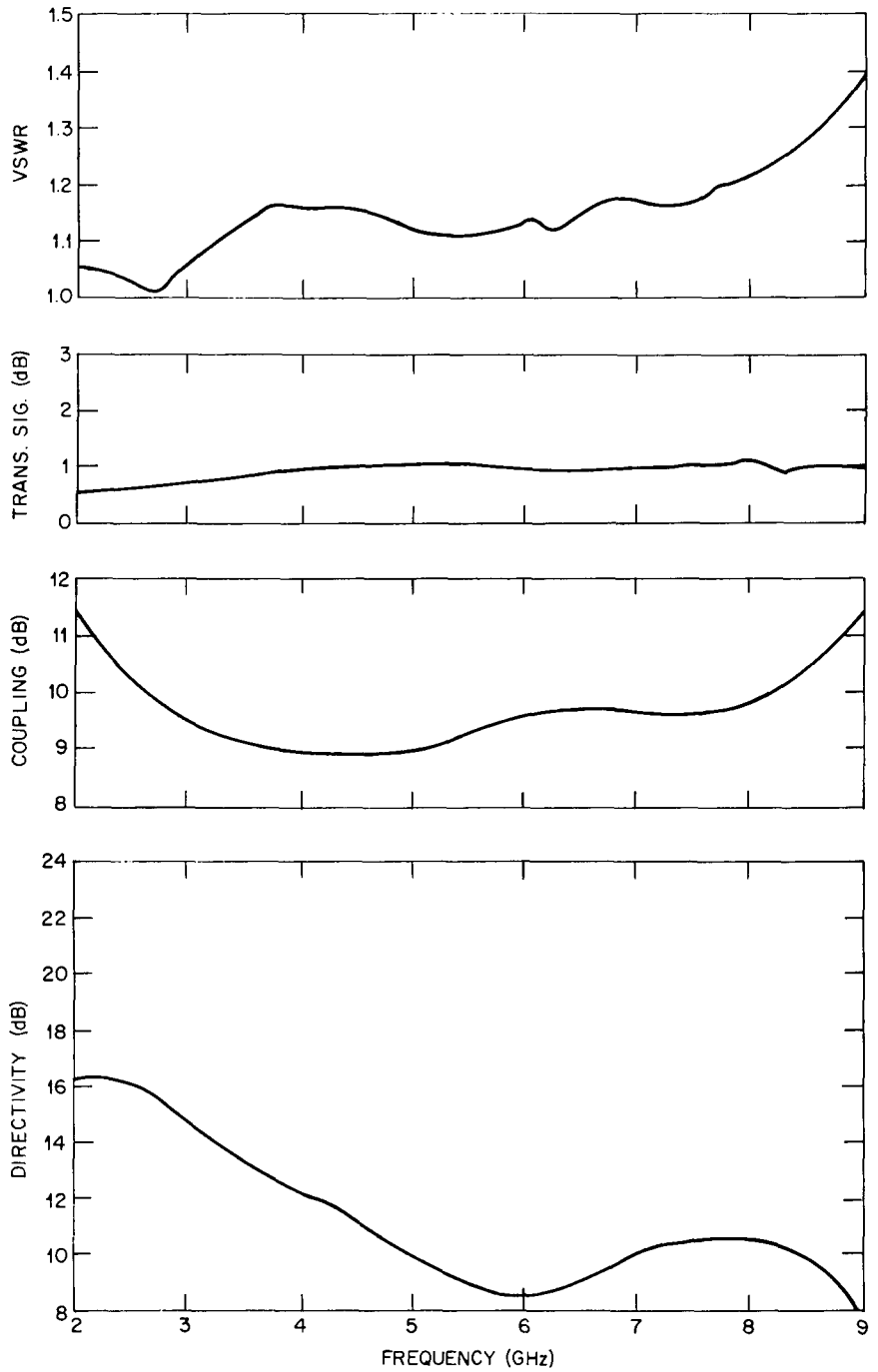

Fig. 5 — 10 dB coupler (first generation)

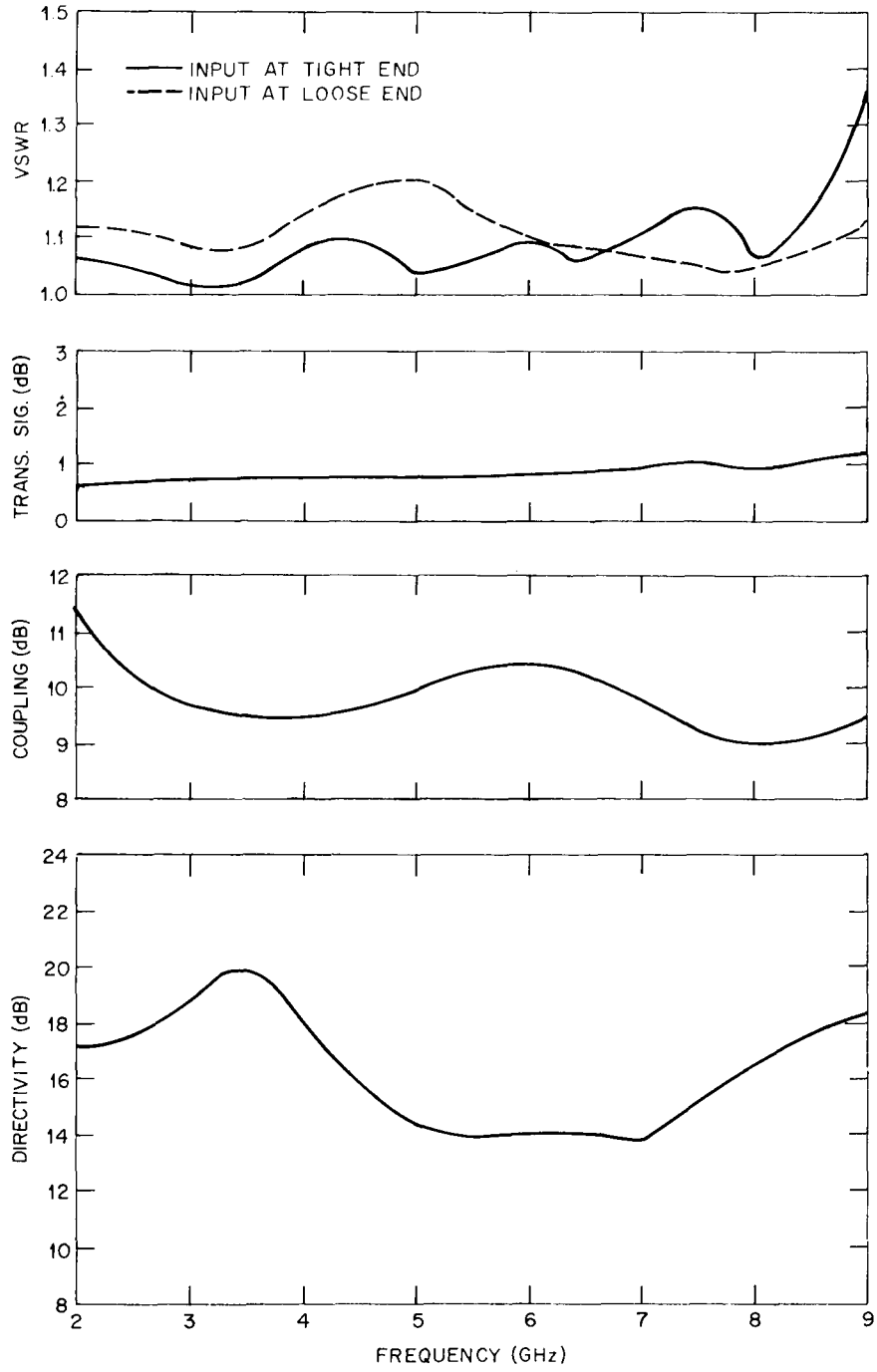

Fig. 6 — 10 dB coupler, systematic (second generation)

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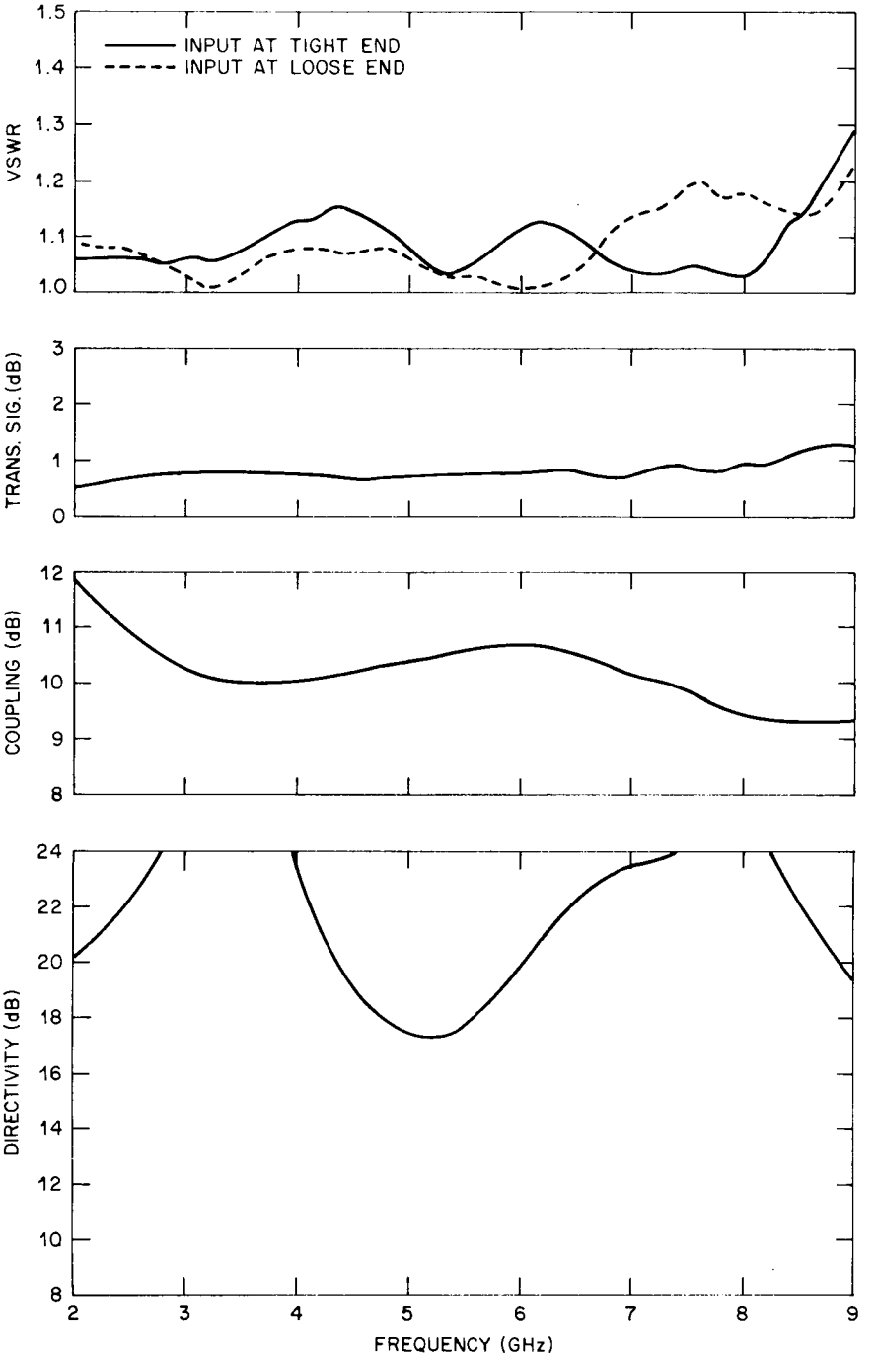

Fig. 7 — 10 dB coupler, tuned (second generation)

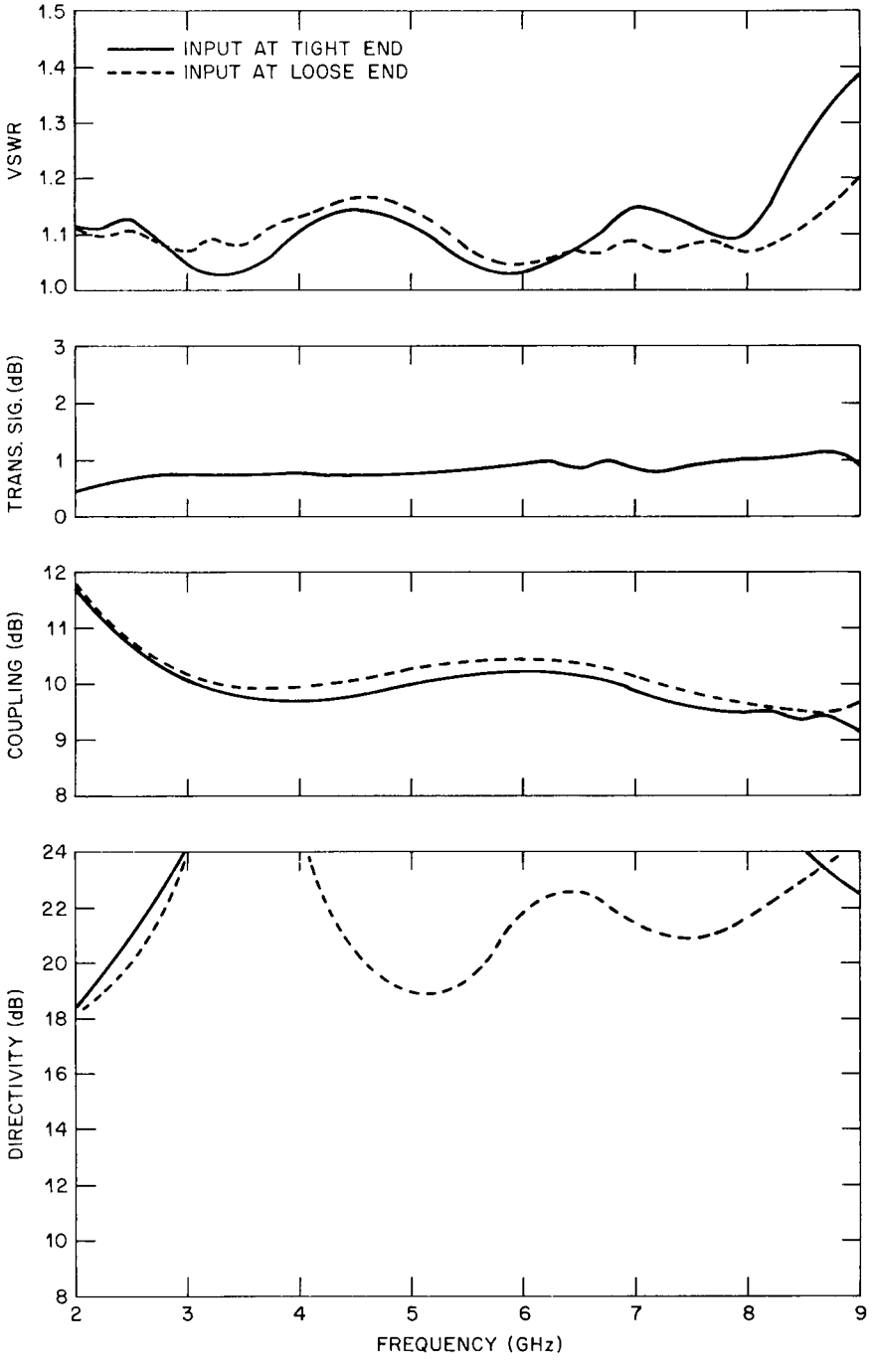

Fig. 8 — 10 dB coupler, systematic (third generation)

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Most of the test results have double curves, which indicate two measurements, one from a port leading to the tight-coupling section and one to a port leading to the loosely coupled section. This is necessary for asymmetric couplers, because if there is a mismatch condition in the intersection-transition region, it will be masked when looking into the tightly coupled section. Once the coupling curve is measured, it will be quite apparent if the coupling values or section lengths need adjustment (Appendix C). No section length changes were made in this investigation, even though it appears that some section lengthening would have been advantageous.

6 dB Coupler

The target coupling performance curve for the 6 dB coupler is shown in Fig. 9. This calculation assumed a 3.5 dB tight section, a 12.9 dB loose section, and 0.5 dB dissipative loss. Figures 10 and 11 give the performance curves of the initial and final design models. Notice that the chief difference between the "tuned" first model and the systematic final model is the directivity. This illustrates clearly that although the coupler isolation can be enhanced by empirical tuning, it is more desirable to do another design iteration. The test results for these devices show that the coupling curves closely approximate the target value of 6.0 ± 0.4 dB.

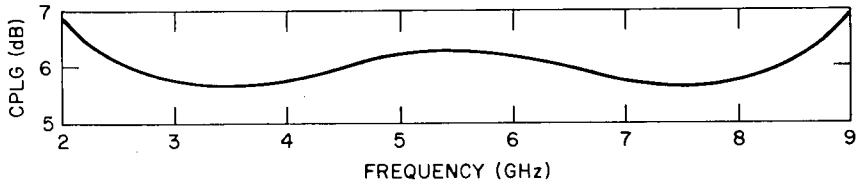

Fig. 9 — Target coupling performance for the 6 dB coupler with 0.55 dB loss compensation. C_1 = 3.5 dB, C_2 = 12.9 dB, and $\ell_1 = \ell_2$ = 0.219 in.

One might ask how critical the fabrication operation is in this design approach, since extremely tight dimensional tolerance is difficult to maintain in production. This problem was addressed by evaluating an over-etched 6 dB coupler, designed in exactly the same manner as the other 6 dB circuits. The test results for this systematic coupler (Fig. 12) indicate a high-performance 6.7 dB coupler. The gap, overetched by about 0.8 mil, loosened the coupling but did not alter other performance characteristics significantly.

20 dB Coupler

The 20 dB coupler proved to be more difficult to develop than either the 10- or 6-dB coupler. The most successful model developed in this effort is characterized by the performance curves of Fig. 13. The coupling ripple is slightly greater than the design-goal performance of Fig. 14, but the overall performance is still of high quality.

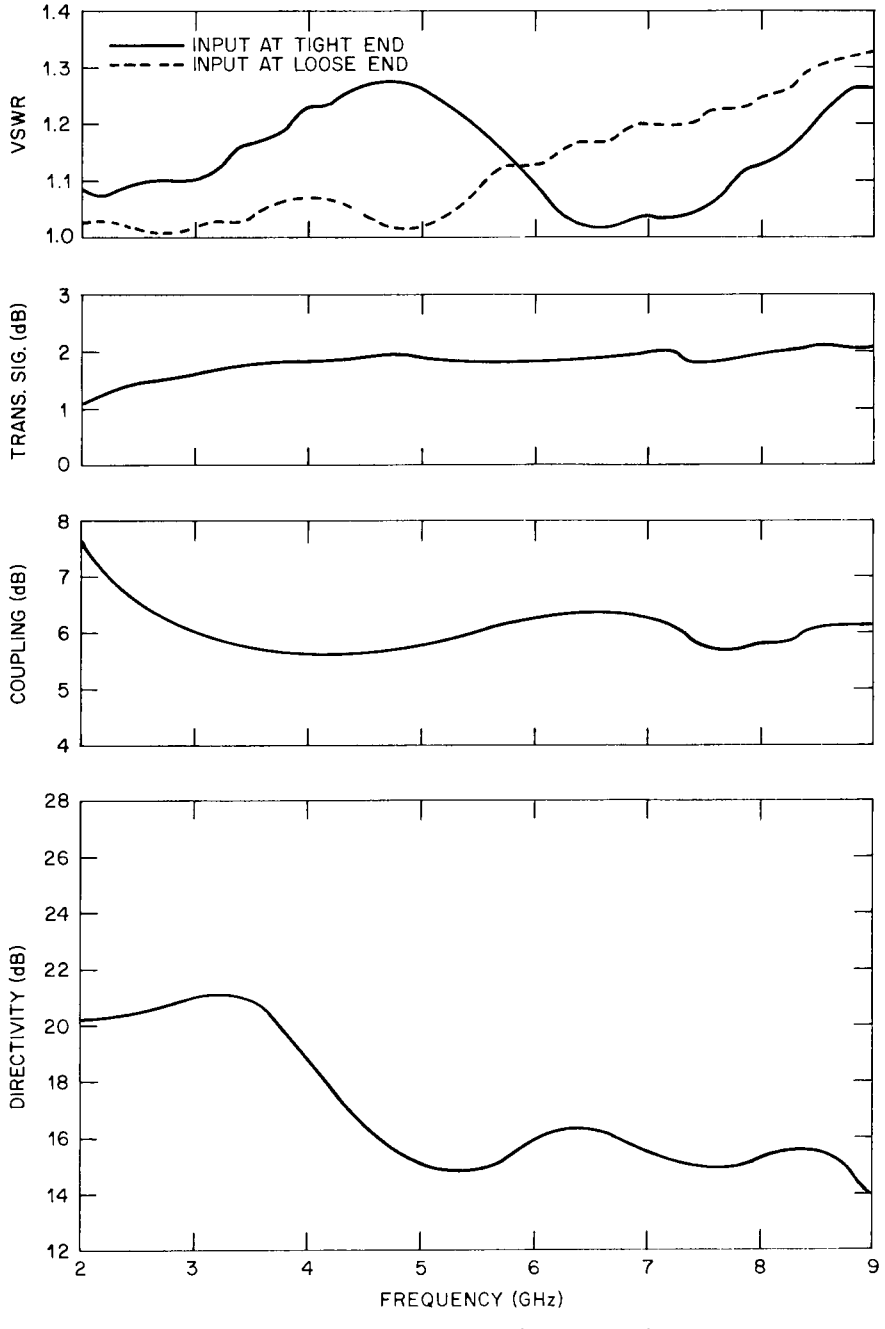

Fig. 10 — 6 dB coupler, tuned (first generation)

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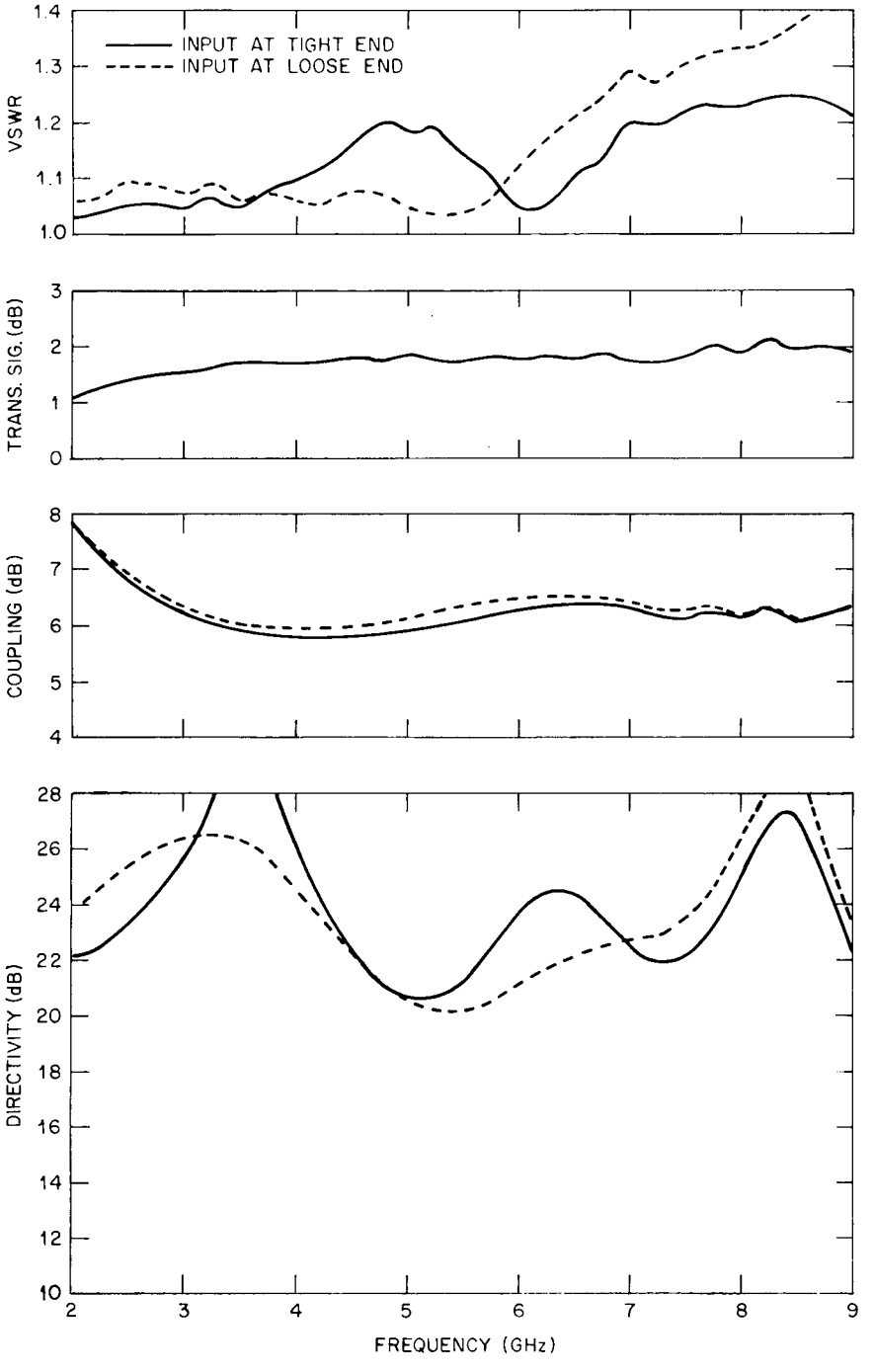

Fig. 11 — 6 dB coupler, systematic (second generation)

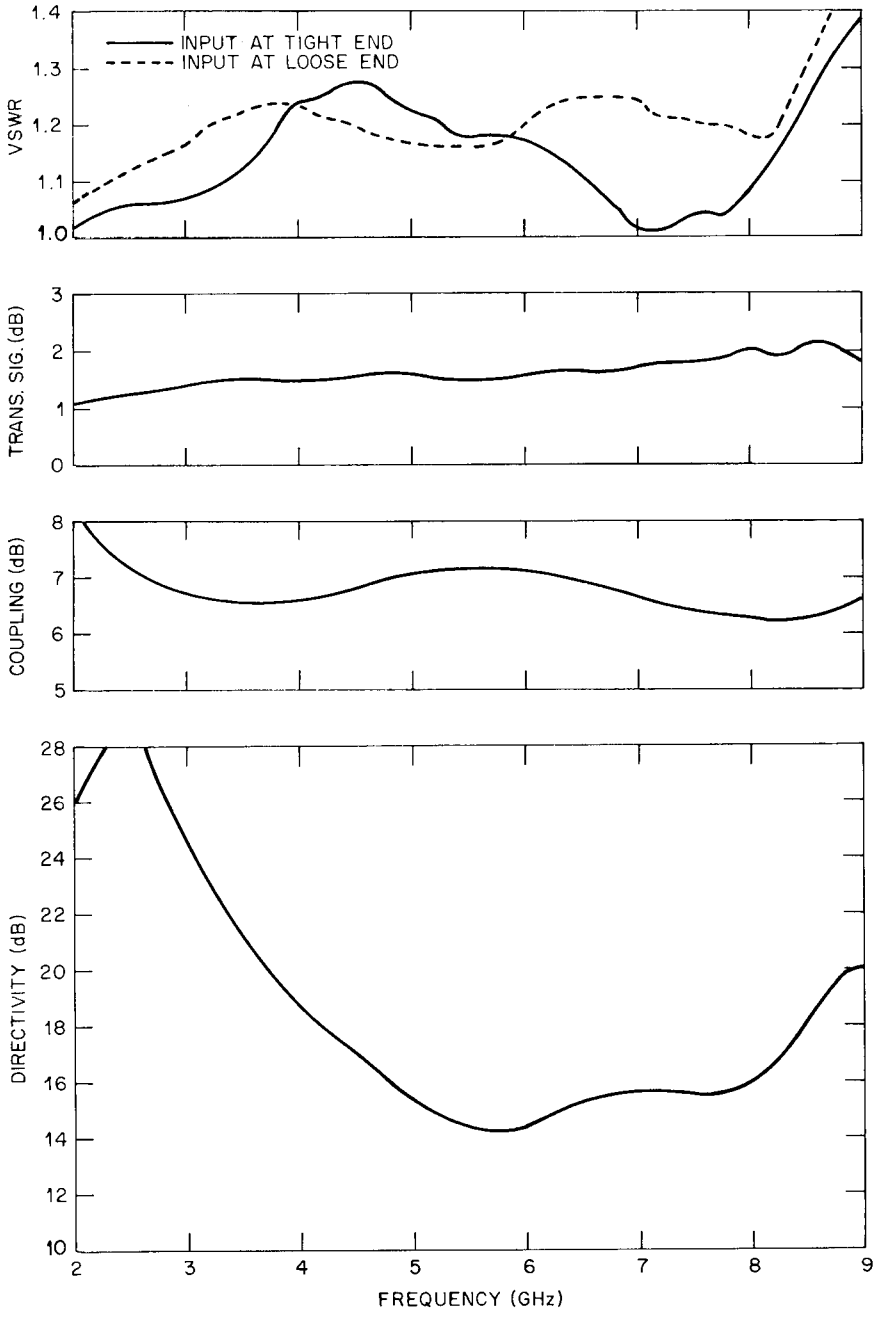

Fig. 12 — 6.7 dB coupler, systematic

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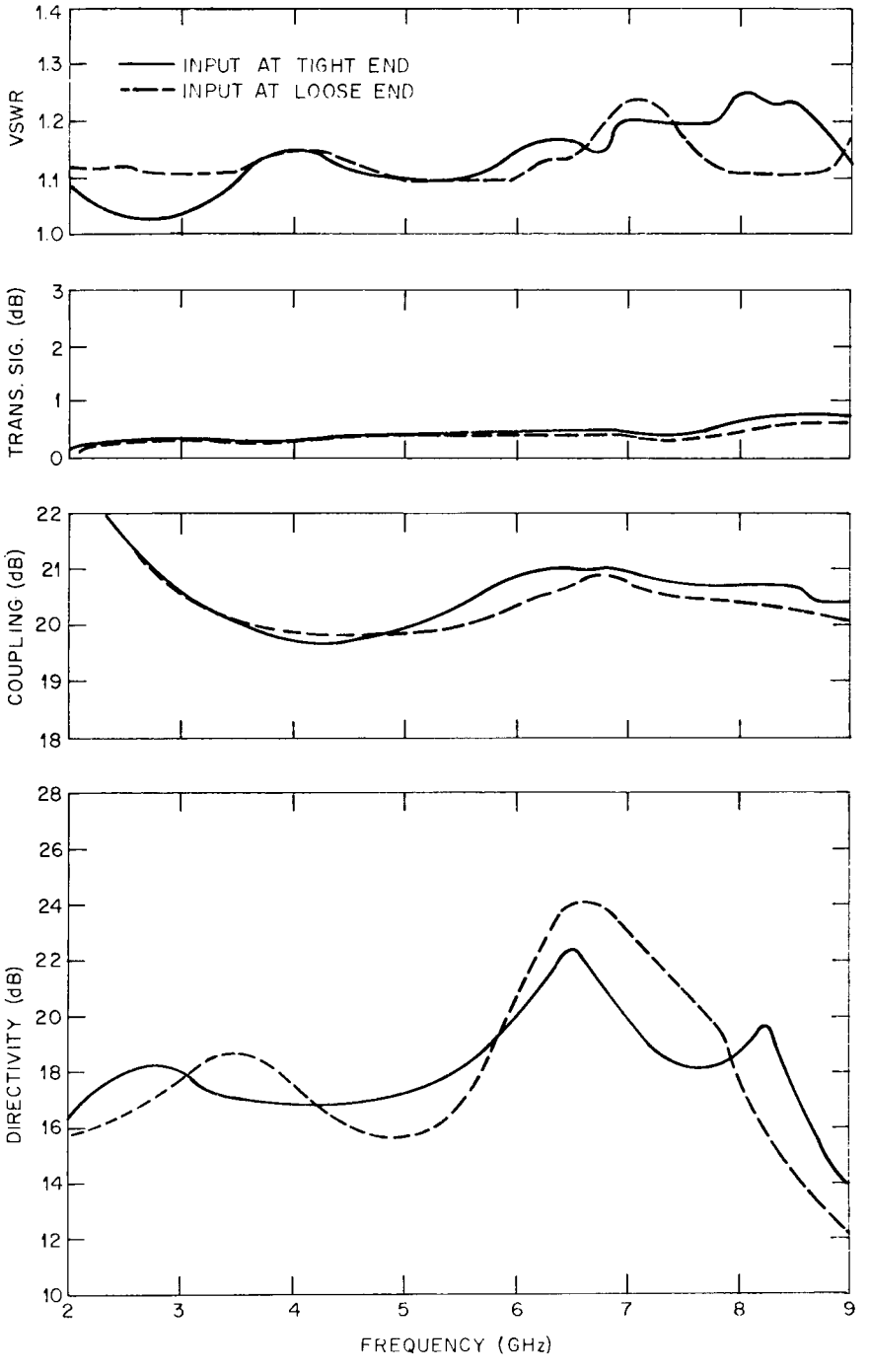

Fig. 13 — 20 dB coupler, systematic (second generation)

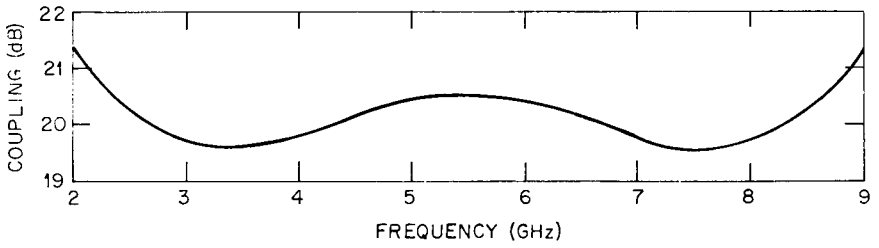

Fig. 14 — Target coupling performance for the 20 dB coupler with 0.5 dB loss compensation. C_1 = 16.9 dB, C_2 = 27.3 dB, $\ell_1 = \ell_2$ = 0.219 in.

A packaging problem arose in the development of the 20 dB coupler that had not occurred before. All of the couplers described heretofore were packaged exactly the same. However, there was a noticeable "box top" effect observed when the 20 dB coupler was housed in the same casing. The box-top height above the etched circuit pattern was 0.135 in., and apparently this was not adequate for this coupler. This proximity effect might be inherent in all overlay couplers with loose-coupling sections. The sectional coupling values for this 20 dB coupler are 16.9 dB and 27.1 dB, which are quite weak coupling values.

Another production consideration is performance repeatability for similar couplers designed and developed by the same technique. To demonstrate this repeatability, two 20 dB directional couplers were fabricated from the same mask. Routine care was used throughout the fabrication and testing operations. The performance evaluations for these two couplers (Fig. 15) clearly demonstrate the production utility of this development technique. Engineering drawings of the circuit patterns for the 6-, 10-, and 20-dB couplers are found in Appendix A. These are the actual drawings used to produce the artwork.

SOME CONSIDERATIONS FOR VERY TIGHT COUPLERS

The success in predictably designing the 6-, 10-, and 20-dB couplers prompted consideration of dielectric-overlay techniques for use in more tightly coupled broadband couplers — specifically, a 3 dB hybrid coupler.

The most obvious approach for achieving tight-coupling levels is to cascade quarter-wavelength ($\lambda/4$)-long sections of the coupled line structures. Computations (program COUPLE) show that a $\lambda/4$-long section with about 1.4 dB coupling is required to design a 3 dB hybrid coupler with 1 dB maximum unbalance over a frequency range 2.5 — 8.5 GHz. As mentioned earlier, results obtained using program MICDOC show that the tightest coupling achievable in a $\lambda/4$ section of dielectric-overlay coupler on 25-mil-thick alumina is 3 dB. This limiting level is attributable partly to current limitations in fabrication tolerances.

The next approach considered was the tandem interconnection of 8.3 dB dielectric-overlay couplers to implement the 3 dB hybrid coupler, as depicted schematically in

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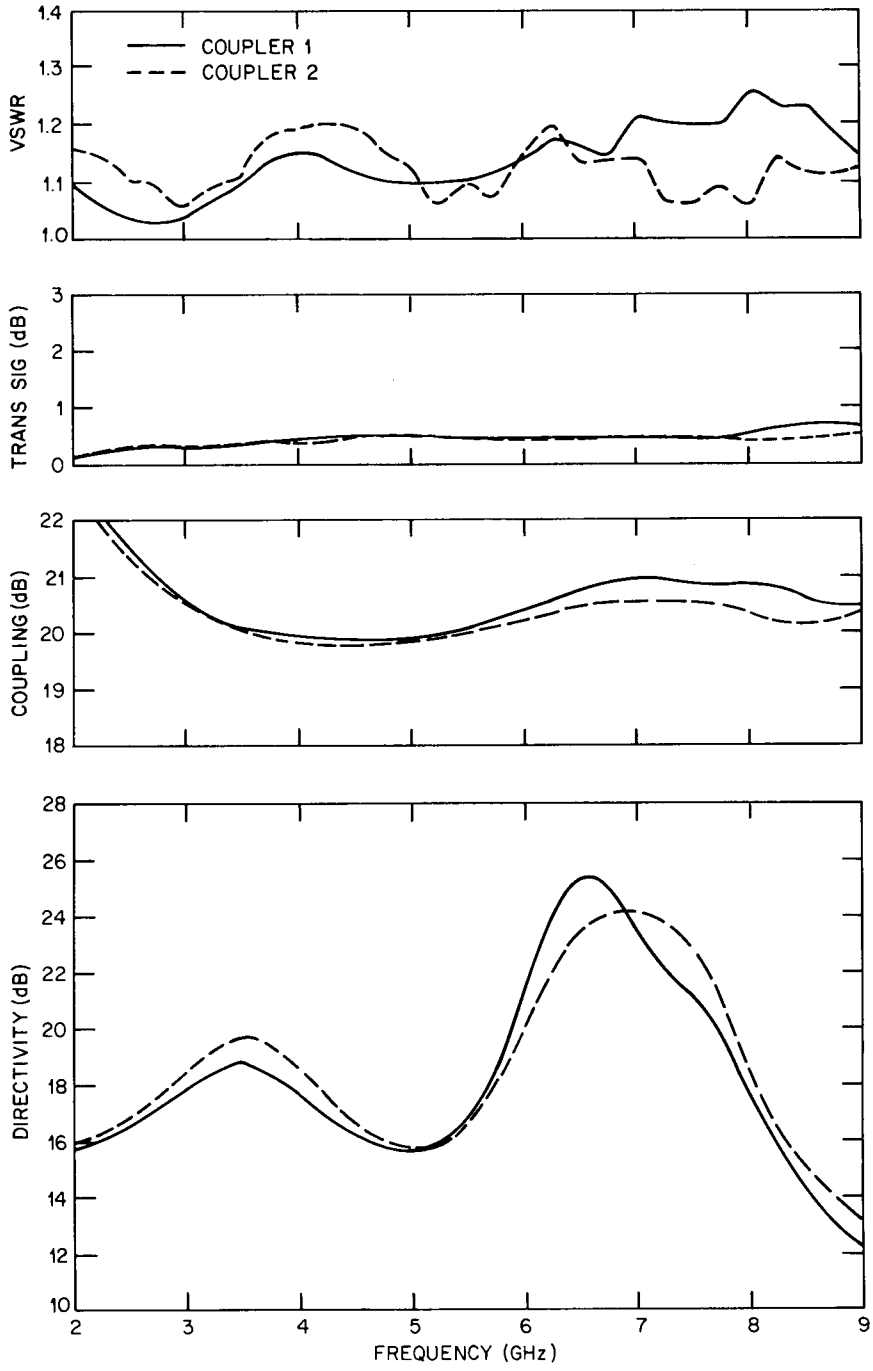

Fig. 15 — 20 dB couplers, systematic (repeatability demonstration)

Fig. 16. As is indicated in this figure, the tandem interconnection of 8.3 dB couplers topologically requires microstrip crossovers in each coupler. The authors were cognizant of a previous investigation [6] which leads to the development of a high-performance, 3 dB hybrid coupler of this type. Over the frequency range 3 — 9 GHz, that coupler had a maximum inbalance of about 0.8 dB. The VSWR was 1.2 or better, the worst case isolation was 20 dB, and the worst case dissipation loss measured about 1.1 dB.

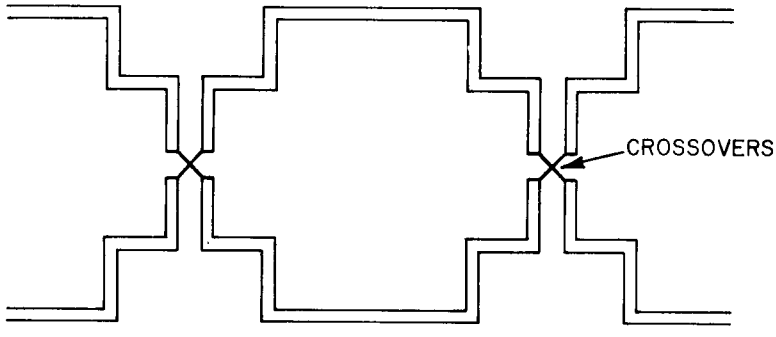

Fig. 16 — Schematic diagram of a 3 dB coupler using two dielectric-overlay 8.3 dB couplers connected in tandem

Improvement of the predictability of the design and repeatability of the performance of this coupler was then considered. Because the design of the coupler just described did not prescribe the positions of the dielectric overlays, empirical tuning by adjusting overlay positions was necessary to obtain good electrical performance. This situation clearly could be improved by appropriately using program MICDOC. Even with this improvement, however, the predictability and repeatability would still be questionable due to the microstrip crossovers necessary for implementing the tandem interconnection of the couplers. The previous effort required time-domain reflectometer (TDR) equipment to incorporate crossovers into the circuit with good electrical performance.

To improve the repeatability of these couplers, it was decided to investigate microstrip crossovers which could be adequately designed and fabricated without resorting to TDR monitoring of performance. Figure 17 shows the crossover chosen as the most promising candidate, based on considerations of symmetry and electrical-design principles.

Two symmetric, three-section, 8.3 dB couplers were built and tested, one with a crossover in the tight section and one without. These couplers were designed to have a 5.6 dB center section and 20.2 dB end sections, producing a calculated resultant coupling characteristic of 8.31 ± 0.36 dB over the band. Figure 18 compares the performance characteristics of these two couplers. The "tilt" in the coupling vs frequency characteristics for the coupler without a crossover is attributable to an effective change in the electrical lengths of the coupler sections due to the intersection transitions. Since these effects must also be present in the coupler with a crossover, the difference in the performance of these couplers is attributable to effects of the crossover. Since empirical tuning is not to be employed, it appears unlikely that a good crossover can be developed

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Fig. 17 — Systematic crossover

without a more thorough study for each coupling value. Also, for the sake of completeness, a nonsymmetrical crossover was tested, and it proved to have performance essentially the same as that of a symmetrical crossover.

In spite of the performance of the individual 8.3 dB coupler with crossovers, investigation of the crossover effect was pursued further by constructing a 3 dB hybrid coupler from them. The measured performance of this coupler is shown in Fig. 19.

It should be noted that this investigation was cursory in nature and is intended to serve only as a guideline for further investigation of tight, broadband couplers.

DISCUSSION

The use of dielectric overlays to improve coupler directivity was first reported on for broadband couplers by Spielman [3]. A design procedure was described that took

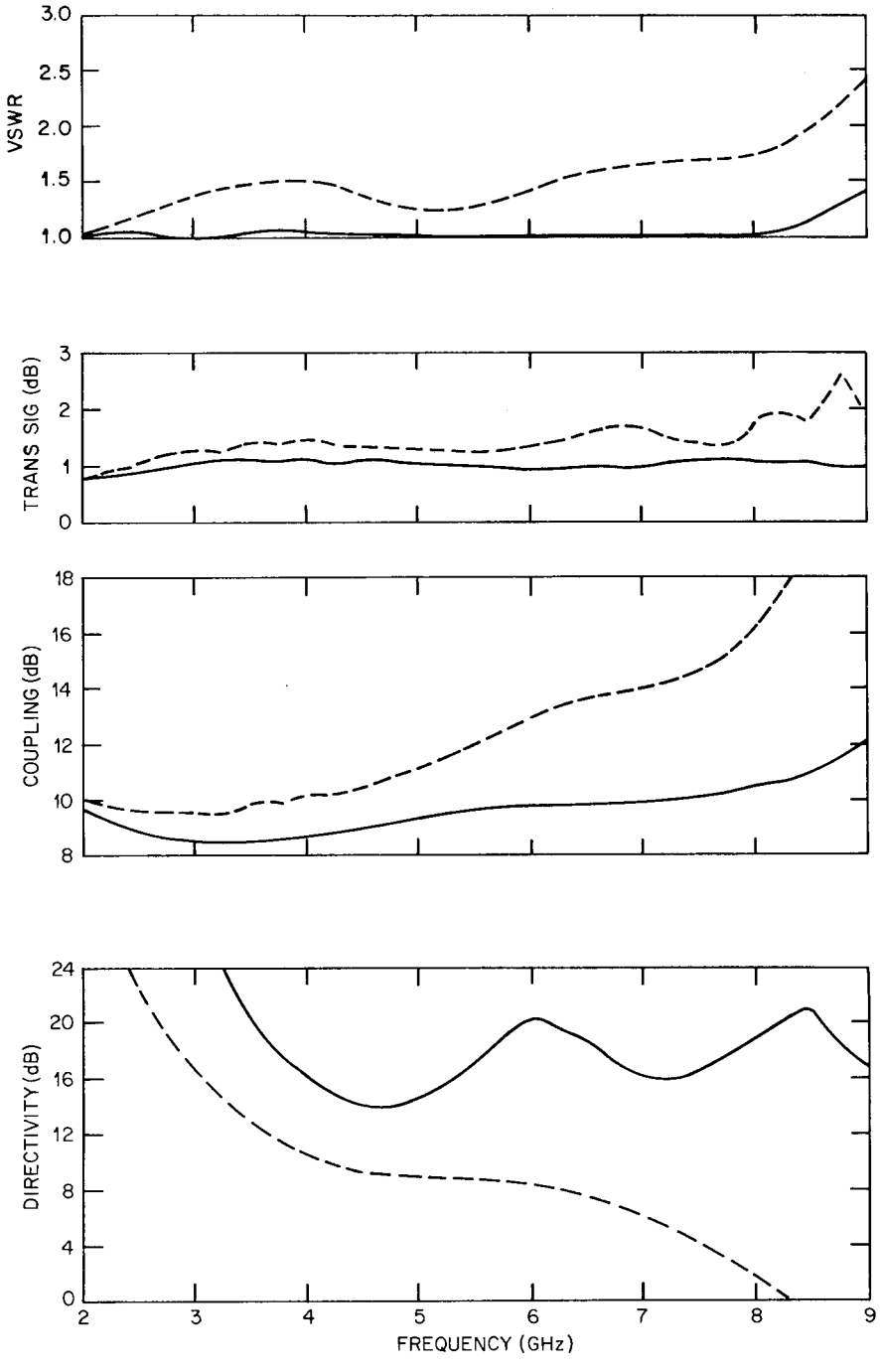

Fig. 18 — 8.3 dB couplers (compares performance of two identical couplers — one with a crossover, one without). Solid line: no crossover; dashed line: with crossover.

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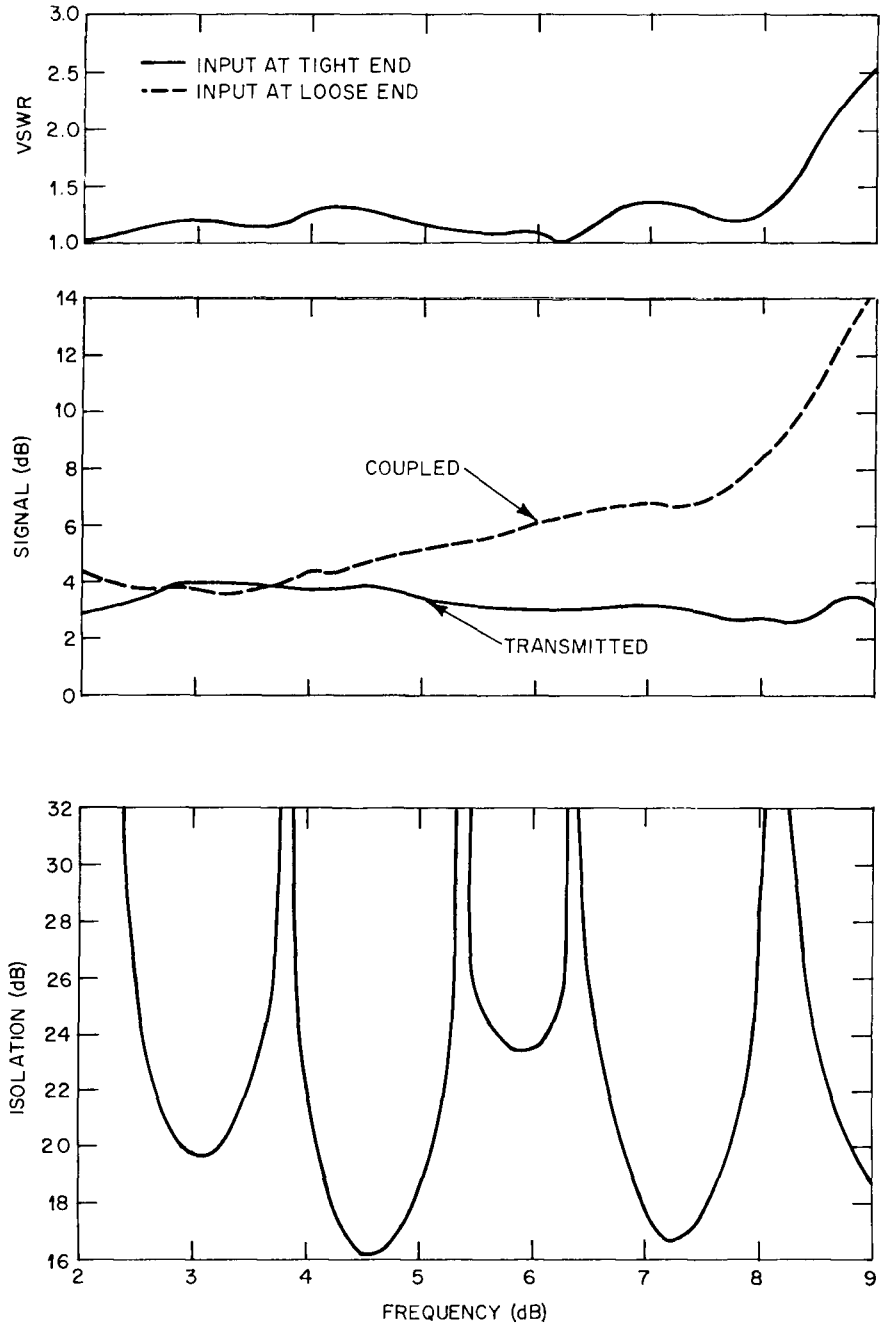

Fig. 19 — 3 dB hybrid coupler

into account the increased coupling caused by the dielectric overlay but neglected the accompanying impedance drop. Consequently, it was usually necessary to painstakingly position the overlays on the coupler while monitoring its performance until a satisfactory compromise was achieved between the directivity and VSWR. The result was a tuned coupler. In Lee's [7] application of coupled microstrip with dielectric (resistive) overlays to directional-filter design, the assumption is made that the "proper" overlay equalizes the modal phase velocities by changing only the odd-mode velocity. The proper overlay geometry and position must be determined empirically. Though this approach offers approximate design information for determining the coupling and impedance in the coupled-line region, the assumption about the behavior of the modal phase velocities is not adequate for loosely coupled lines and broad frequency bands. This leads to inaccuracies in the coupling level, impedance, and electrical length of the coupled-line region. Buntschuh [6] formulates a design procedure based on an empirically derived formula for effective dielectric constant in the coupled region. This formula gives approximate design information for coupling, impedance, and electrical length for the nondispersive case. Much of this design approach is presented in useful graphical design curves. Again, this procedure requires "tuning" to achieve broadband, high-performance characteristics.

The design approach described in this report can be characterized as follows: The coupling and impedance of the coupling region are accurately specified by using MICDOC, a quasi-TEM computer analysis program, for $\lambda/4$-long coupling sections. This analysis does not account for dispersive effects because it invokes a zero-frequency model; therefore the electrical-length dispersion is not computed. All coupler-geometry parameters (line widths, gap, and overlay dimensions and location) are determined precisely by computer for the circuit pattern. This permits each $\lambda/4$-long coupling section to be designed independently. Nevertheless, one empirical determination does remain — that of optimizing the overlay thickness to achieve high directivity. The distinguishing feature of this operation is that it is a systematic empirical procedure that needs only to be performed on the prototype of each model.

More design information is needed which relates the overlay thickness required for directivity optimization to coupling and frequency. Also lacking is design information which relates the coupled-line electrical length to overlay thickness and includes the dispersive effects. This information, together with the computer-aided analysis described earlier, will greatly facilitate the systematic design of the desired couplers, filters, and phase shifters which use interconnection of coupled-line sections of microstrip with dielectric overlays.

Other design considerations should be mentioned. First, the intersection transition connecting the multicoupling sections is very important. A poorly matched transition can cause problems with the isolation, coupling section length, and input impedance. Caution should be exercised in symmetric couplers where adverse transition effects tend to be masked. It was found that the most successful intersection transitions were those which had their center lines almost perpendicular to the coupled microstrip lines.

Second, the coupling section length is difficult to precisely predict because it is affected by the dielectric overlay, intersection transition, and mitered corners [8] at the coupling region. The electrical length did not seem to change appreciably when

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systematic couplers were tuned with partial overlays. Usually, one design iteration is sufficient to determine the proper electrical length of the section.

Third, there are definite limits on the coupling values. It was calculated that for a 25-mil-thick substrate and a coupling gap of 1.0 mil, which requires care to fabricate, the tightest coupling obtainable would be less than 3 dB, regardless of the overlay thickness. Smaller size gaps are possible, but the fabrication problems become horrendous for 250-μin. metalization thickness, especially in production. It was this coupling limitation which precluded the 3 dB hybrid coupler from this discussion. On the other hand, for very loose coupling ($<$ 18 dB) some unusual performance behavior is observed. Prior mention was made of the "box top" effect encountered with the 20 dB directional coupler. When the individual 27.1 dB coupling section was examined, its performance also exhibited some adverse effects. Certainly, for a weak coupler the effects of various mismatches and termination quality become pronounced. Also, "box top" proximity effects tend to become more significant for looser couplers.

Finally, investigation of the interdependence of overlays in multisection couplers could result in either the elimination of overlays on some coupled sections or in a relaxation of fabrication problems caused by overlays that have unpractical dimensions.

CONCLUSION

A computer-aided, systematic, design technique was used successfully to develop a class of high-performance, broadband, MIC couplers with dielectric overlays.

Three directional couplers (6 dB, 10 dB, and 20 dB) were designed, fabricated, and evaluated. The measured and predicted performance characteristics of these couplers showed good agreement. This design approach is characterized by prescribed locations for the dielectric overlays, an essential operation for use in integrated systems. The systematic development of these directional couplers, which precludes individual tuning, makes them especially suitable for large-quantity production.

ACKNOWLEDGMENT

The authors sincerely thank Max L. Reuss, Jr., for his numerous valuable comments and suggestions.

REFERENCES

1. A. Podell, "A High Directivity Microstrip Coupler Technique," *G-MTT* 1970 *International Microwave Symposium, Digest of Papers*, Newport Beach, CA, May 11-14, 1970, p. 33.

2. R. Levy, "Tables for Asymmetric Multi-Element Coupled-Transmission-Line Directional Couplers," IEEE Trans. Microwave Theory Tech., *MTT*-12, 275 (1964).

3. B.E. Spielman, "The Development of a 20 dB Directional Coupler for MIC Applications," presented to 1973 *IEEE-GMTT International Microwave Symposium*, June 4-6, 1973, Univ. of Colorado, Boulder, CO.

4. R.A. Pucel et al., "Losses in Microstrip," IEEE Trans. Microwave Theory Tech., *MTT*-16, No. 6, 342 (1968).

5. B.E. Spielman, "Analysis of Electrical Characteristics of Edge-Coupled Microstrip Lines with a Dielectric Overlay," NRL Report 7810, Oct. 25, 1974.

6. C. Buntschuh, "Octave-Bandwidth Microstrip," *RADC*-74-396, Rome Air Development Center, Rome, NY, Contract F30602-72-C-0282, Jan. 1974 (AD 777320).

7. Y.S. Lee, "Mode Compensation Applied to Parallel-Coupled Microstrip Directional Filter Design," IEEE Trans. Microwave Theory Tech., *MTT*-22, 66 (1974).

8. D. Kelley et al., "Microstrip Filters and Couplers," IEEE Trans. Microwave Theory Tech., *MTT*-16, 560 (1968).

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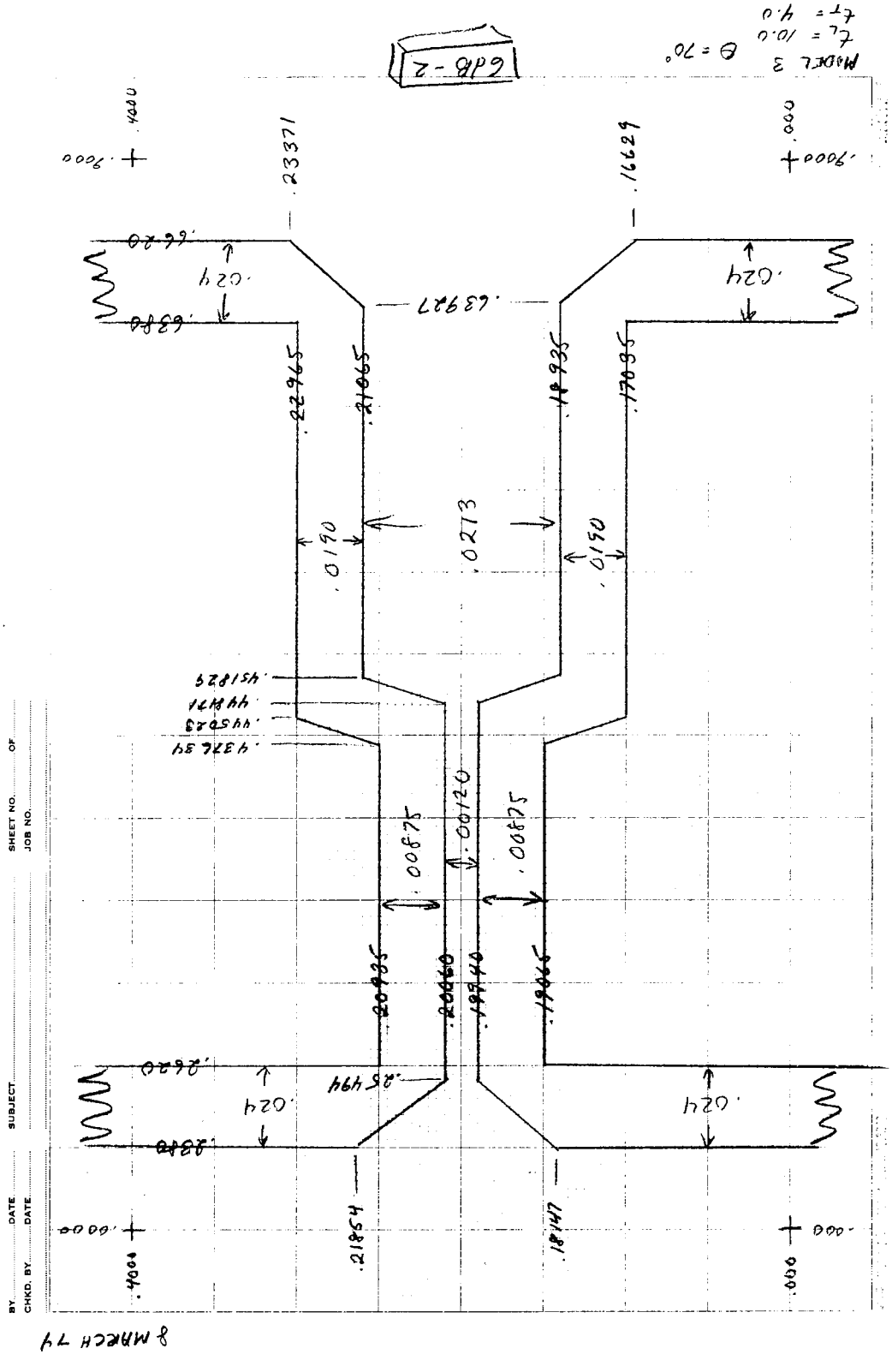
Appendix A
ENGINEERING DRAWINGS


6dB-2
MODEL 3
θ = 70°
.23371
.16629
.63927
.22965
.21065
.18935
.17035
.0190
.0213
.0190
.00875
.00120
.00875
.20935
.20060
.19940
.19065
.21854
.18147
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.9000
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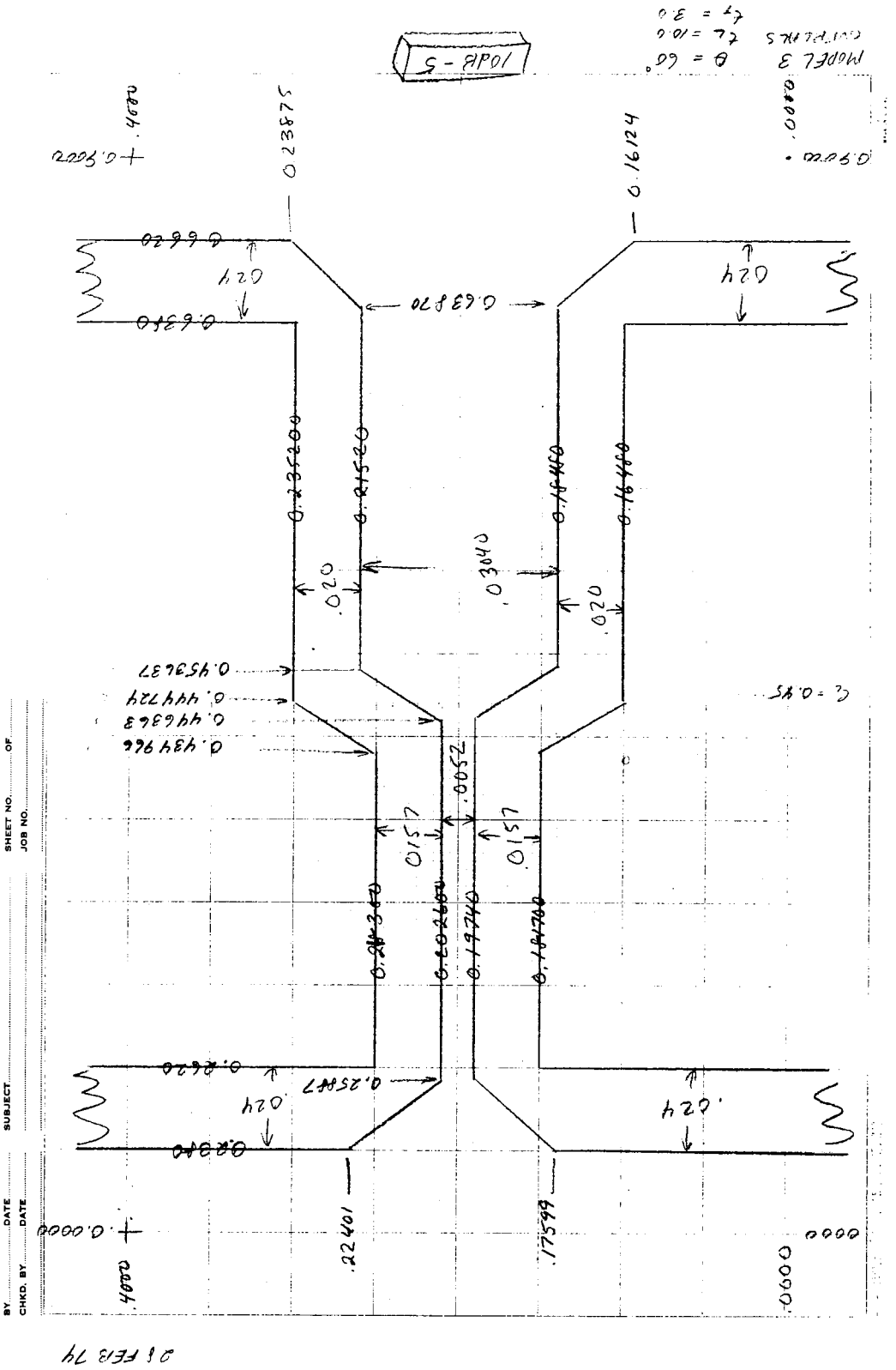

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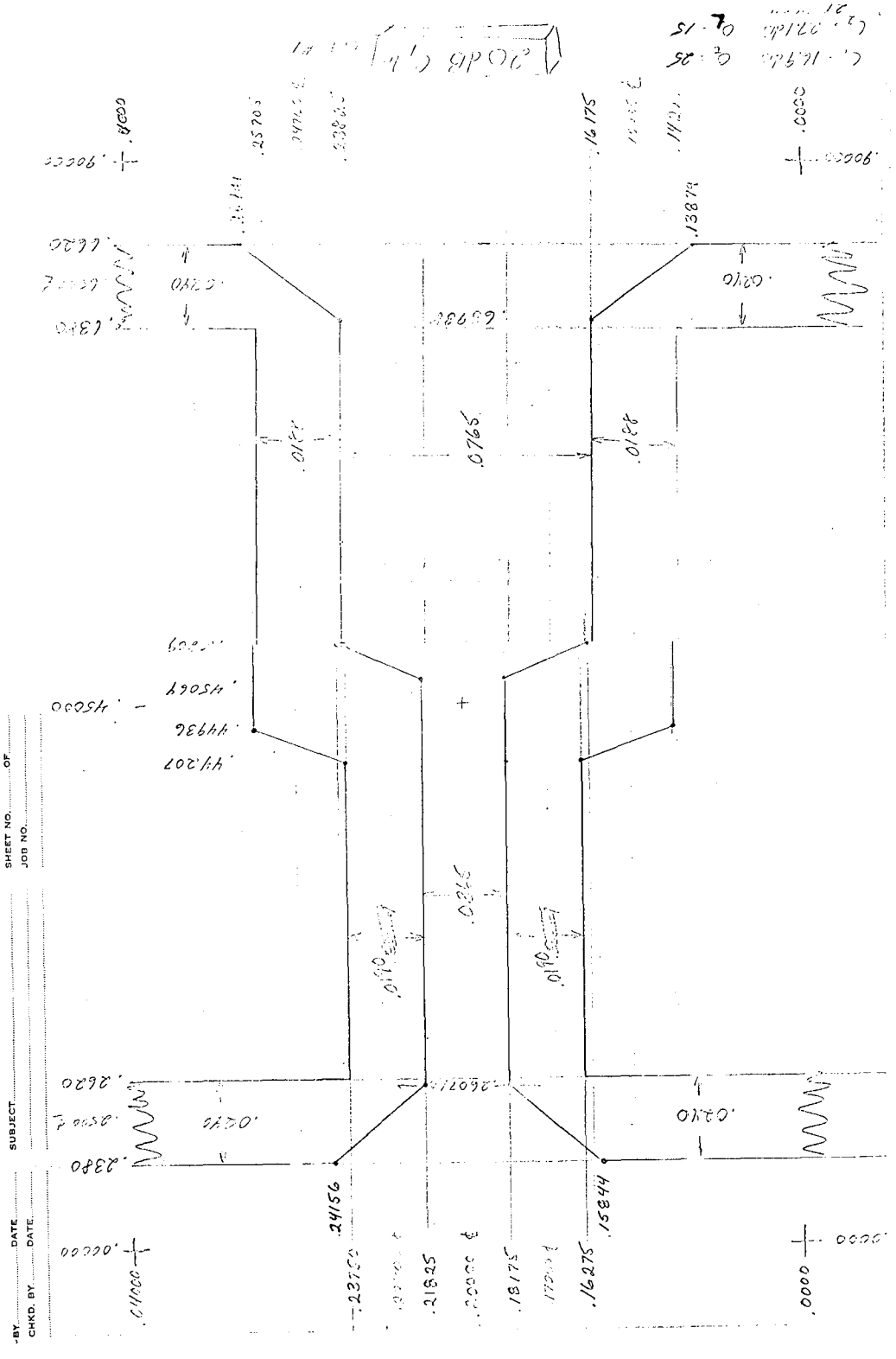
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Appendix B

DESCRIPTION AND LISTING OF THE PROGRAM (COUPLE) FOR CALCULATING THE COUPLING CURVES FOR TWO-SECTIONS, ASYMMETRIC COUPLERS

Given the sectional coupling and length values for a two-section asymmetric directional coupler, the coupling performance curve can be calculated as follows: Let

C_1 = coupling value (voltage ratio) of section 1,

C_2 = coupling value (voltage ratio) of section 2,

ℓ_1 = length (meters) of section 1,

ℓ_2 = length (meters) of section 2,

F = frequency (Hz),

and

$v = 1.2 \times 10^8$ m/s.

The even-mode impedance Z_{0e} for the first section can be expressed as

$$\frac{(Z_{0e})_1}{Z_0} = \left(\frac{1 + C_1}{1 - C_1}\right)^{1/2},$$

where Z_0 is the characteristic impedance. Similarly, for the second section the even-mode impedance is

$$\frac{(Z_{0e})_2}{Z_0} = \left(\frac{1 + C_2}{1 - C_2}\right)^{1/2},$$

and thus

$$\frac{(Z_{0e})_2}{(Z_{0e})_1} = \left[\frac{(1 + C_2)\,(1 - C_1)}{(1 - C_2)\,(1 + C_1)}\right]^{1/2}.$$

An ABCD matrix approach yields

$$X_1 = \cos\theta_1 \cos\theta_2 - \sin\theta_1 \sin\theta_2 \,[(Z_{0e})_1/(Z_{0e})_2]$$

$$X_2 = \frac{(Z_{0e})_2}{Z_0} \cos\theta_1 \sin\theta_2 + \frac{(Z_{0e})_1}{Z_0} \sin\theta_1 \cos\theta_2,$$

$$X_3 = \frac{Z_0}{(Z_{0e})_1} \sin\theta_1 \cos\theta_2 + \frac{Z_0}{(Z_{0e})_2} \cos\theta_1 \sin\theta_2,$$

and

$$X_4 = \cos\theta_1 \cos\theta_2 - \frac{(Z_{0e})_2}{(Z_{0e})_1} \sin\theta_1 \sin\theta_2,$$

where

$$\theta_1 = \frac{2\pi\ell_1 F}{v}, \quad \theta_2 = \frac{2\pi\ell_2 F}{v}.$$

If we let

$$U_1 = X_1 = X_4,$$

$$U_2 = X_1 - X_4,$$

$$V_1 = X_2 + X_3,$$

and

$$V_2 = X_2 = X_3,$$

the resulting coupling (voltage ratio) can be expressed as

$$C = \sqrt{\frac{(U_1 U_2 + V_1 V_2)^2 + (V_2 U_1 - U_2 V_1)^2}{U_1^2 + V_1^2}}$$

or in decibels as

$$C_{\mathrm{dB}} = -20 \log_{10} C.$$

A listing of the computer program follows.

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```
90   REM: "PROGRAM COUPLE (BASIC)"
91   REM: "CALCULATES THE COUPLING CURVE FOR TWO
92   REM:  SECTION ASYMMETRIC COUPLERS"
93   REM: "INPUT C1 AND C2 AS VOLTAGE RATIOS"
94   REM: "INPUT L1 AND L2 IN INCHES"
95   REM: "F2=FIRST FREQ(GHZ)"
96   REM: "F3=LAST FREQ(GHZ)"
97   REM: "F4=FREQ INCREMENT(GHZ)"
99   PRINT "INPUT C1,C2,L1,L2,F2,F3,F4"
100   INPUT C1,C2,L1,L2,F2,F3,F4
101   PRINT "TIGHT SECT CPLG";C1;"LENGTH";L1
102   PRINT "LOOSE SECT CPLG";C2;"LENGTH";L2
103   PRINT F2;"GHZ TO";F3;"GHZ IN STEPS OF";F4;"GHZ"
104   PRINT "FREQUENCY      COUPLING"
110   LET C1=10↑(C1/-20)
120   LET C2=10↑(C2/-20)
121   LET L1=L1*2.54/100
122   LET L2=L2*2.54/100
130   LET V=1.2*10↑8
140   LET A1=SQR((1+C1)/(1-C1))
150   LET A2=SQR((1+C2)/(1-C2))
160   LET A3=A2/A1
170   FOR F=F2 TO F3 STEP F4
180   LET F1=F*10↑9
190   LET T1=2*3.14159*L1*F1/V
200   LET T2=2*3.14159*L1*F1/V
210   LET X1=COS(T1)*COS(T2)-(A1/A2)*SIN(T1)*SIN(T2)
220   LET X2=A2*COS(T1)*SIN(T2)+A1*SIN(T1)*COS(T2)
230   LET X3=(1/A1)*SIN(T1)*COS(T2)+(1/A2)*COS(T1)*SIN(T2)
240   LET X4=COS(T1)*COS(T2)-(A2/A1)*SIN(T1)*SIN(T2)
250   LET U1=X1+X4
260   LET U2=X1-X4
270   LET U3=X2+X3
280   LET U4=X2-X3
290   LET C=SQR((U1*U2+U3*U4)↑2+(U4*U1-U2*U3)↑2)
300   LET C=C/(U1↑2+U3↑2)
310   LET C=(-20/2.30259)*LOG(C)
320   PRINT F,C
330   NEXT F
340   END
```

TIGHT SECT CPLG7 LENGTH.2
LOOSE SECT CPLG16.1 LEGNTH.2
1 GHZ TO5.5 GHZ IN STEPS OF.25 GHZ

FREQUENCY	COUPLING
1	15.5952
1.25	13.9047
1.5	12.6165
1.75	11.6175
2	10.8389
2.25	10.2358
2.5	9.77669
2.75	9.43913
3	9.20613
3.25	9.0645
3.5	9.00335
3.75	9.01295
4	9.08367
4.25	9.20491
4.5	9.36411
4.75	9.54589
5	9.73184
5.25	9.90113
5.5	10.0326

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Appendix C
COUPLING CHARACTERISTICS FOR TWO- AND THREE-SECTION COUPLERS

A set of coupling curves was calculated for the asymmetric two-section coupler and the symmetric three-section coupler. These calculations show the effect of section-length and section-coupling-level changes on the coupling performance curve. The coupler models are shown in Figs. C1 and C2, where the tight-section length and coupling are denoted by L_1 and C_1 and the loose-section length and coupling are denoted by L_2 and C_2. In each set of curves (Fig. C3 — C10) the reference curve is the case when the sectional lengths are $\lambda/4$ at midband frequency. In each figure the coupling for each section is given in decibels and the sectional length in mils.

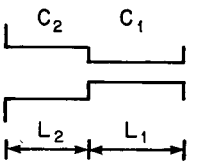

Fig. C1 — Asymmetric two-section coupler

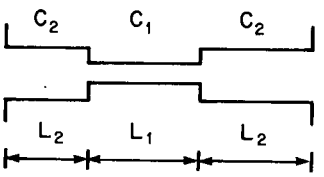

Fig. C2 — Symmetric three-section coupler

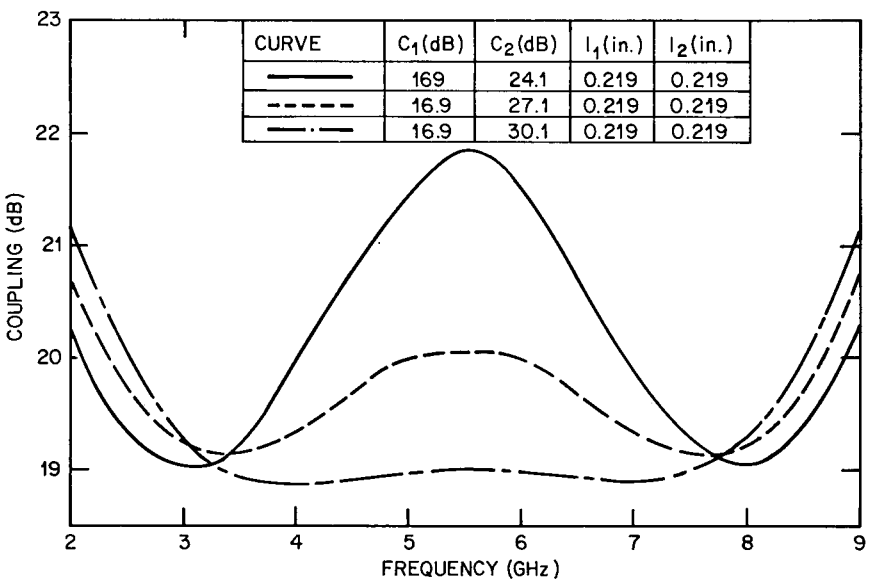

Fig. C3 — Asymmetric coupler — effect of changes in loose-section midband coupling on coupling vs frequency characteristic

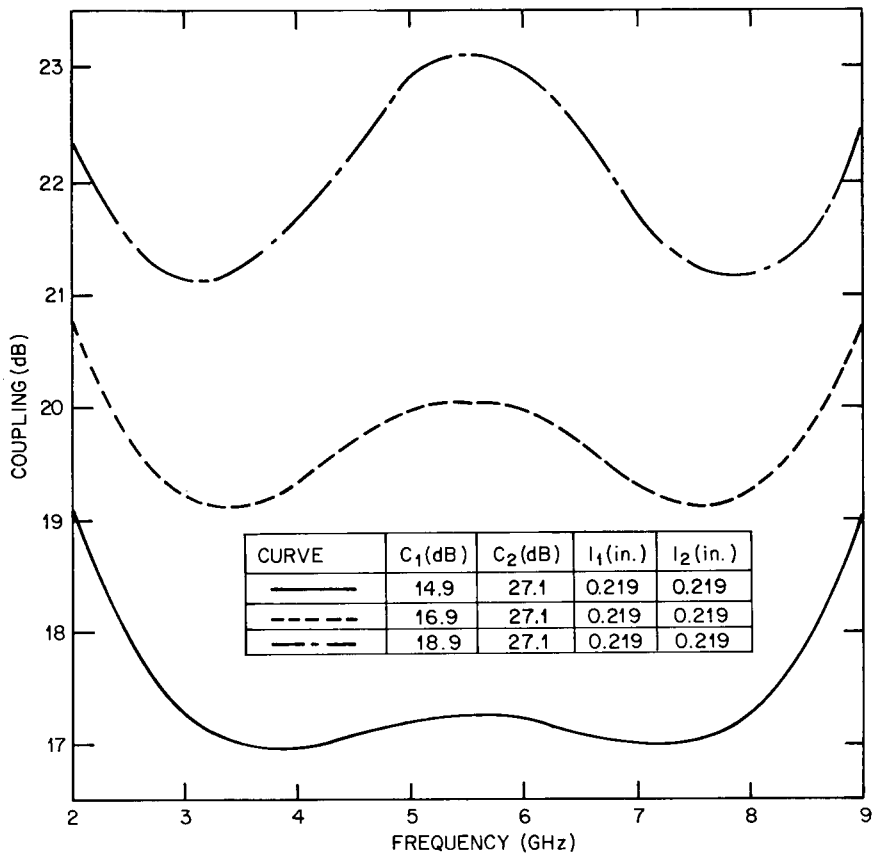

Fig. C4 — Asymmetric coupler — effect of changes in tight section midband coupling on coupling vs frequency characteristic

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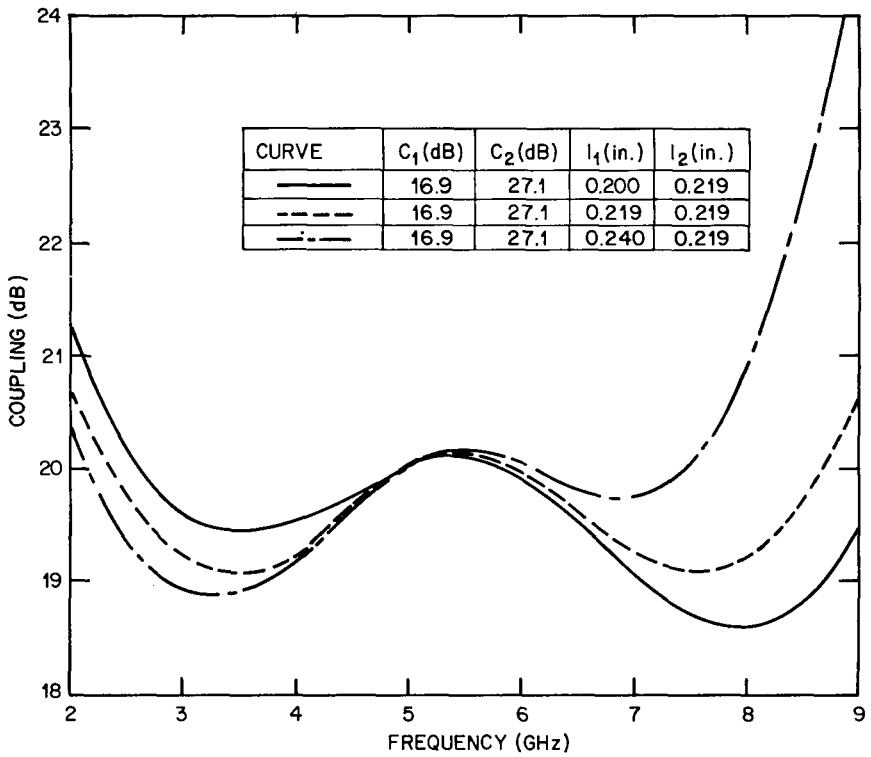

Fig. C5 — Asymmetric coupler — effect of changes in tight section length on coupling vs frequency characteristic

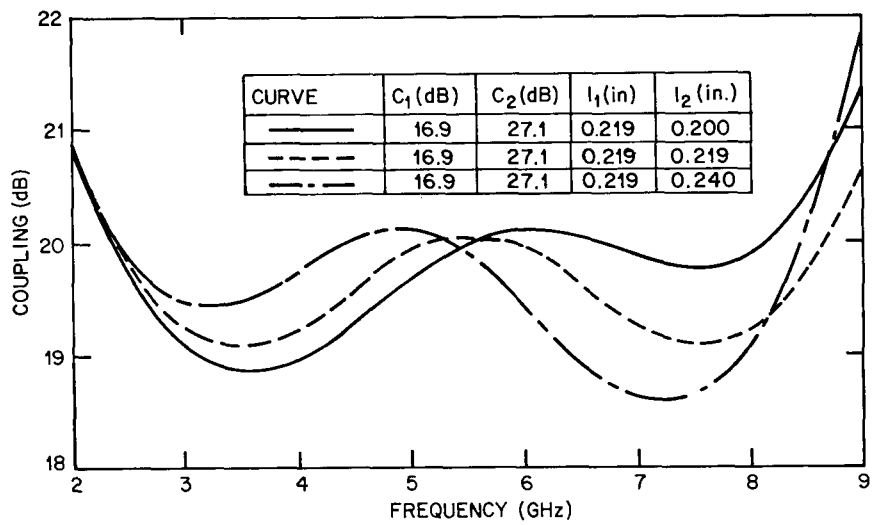

Fig. C6 — Asymmetric coupler — effect of changes in loose section length on coupling vs frequency characteristic

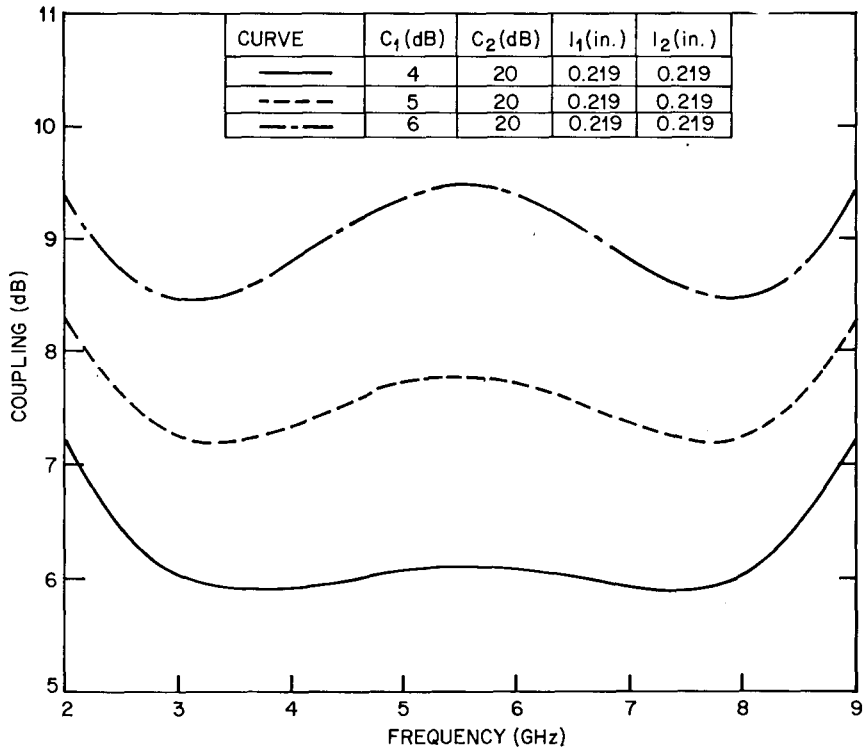

Fig. C7 — Symmetric coupler — effect of changes in tight section midband coupling on coupling vs frequency characteristics

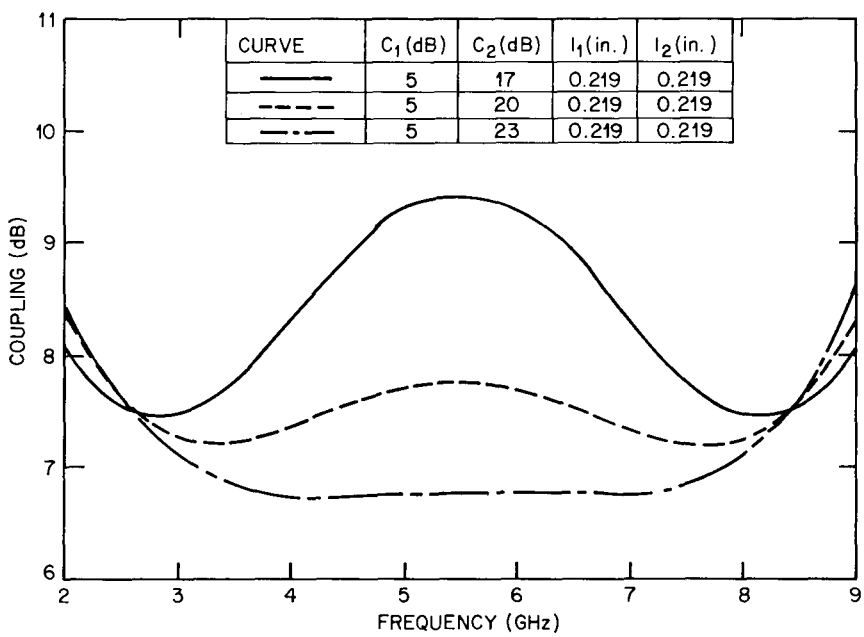

Fig. C8 — Symmetric coupler — effect of changes in loose section midband coupling on coupling vs frequency characteristic

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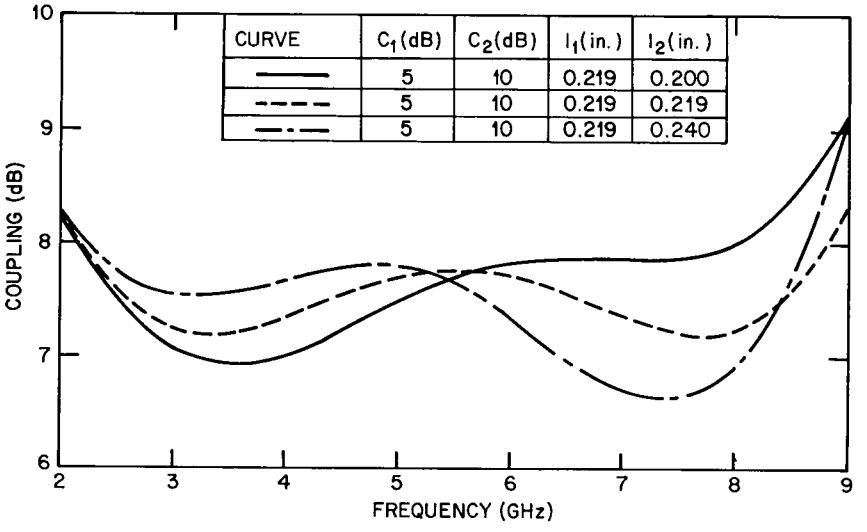

Fig. C9 — Symmetric coupler — effect of changes in loose section length on coupling vs frequency characteristic

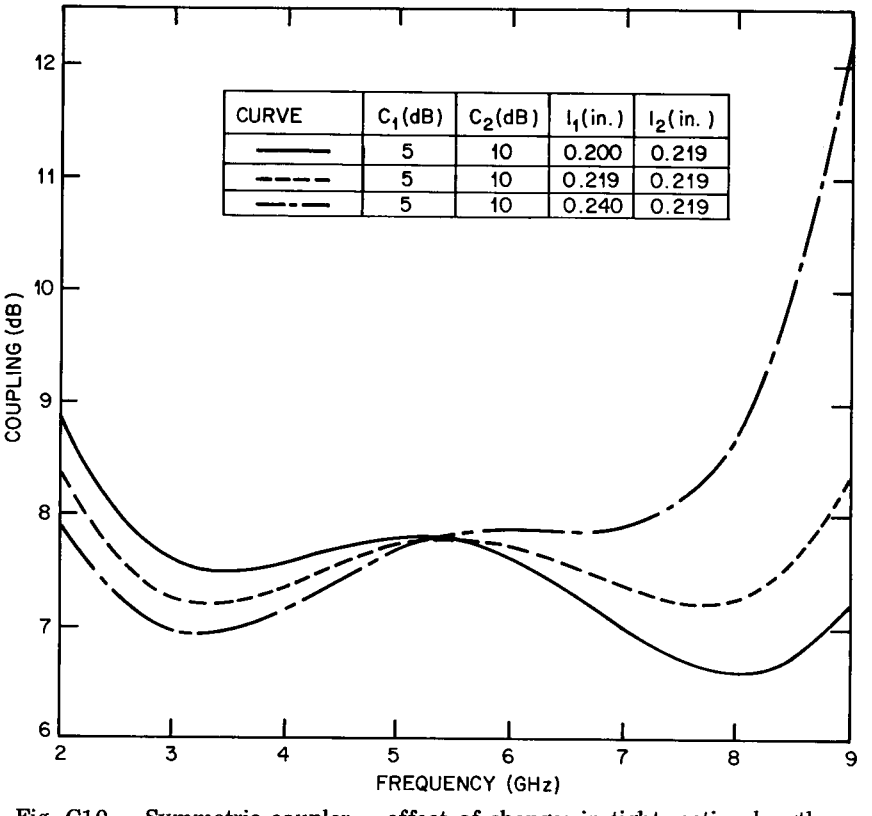

Fig. C10 — Symmetric coupler — effect of changes in tight section length on coupling vs frequency characteristic