Integration of CPW Quadrature Couplers in Multilayer Thin-Film MCM-D

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***Abstract*—In this paper, the design, integration, and measurement of quadrature couplers integrated in a multilayer thin-film multichip-module technology are discussed. We have investigated four- and six-finger coplanar-waveguide (CPW) Lange couplers and a coupler based on reentrant sections. Three methods for the design of CPW Lange couplers are compared for the first time. The method of Paolino consistently results in the best performance. The four-finger Lange coupler results in a −3.2+/−0.2-dB coupling bandwidth from 10.8 to 14.9 GHz, with a return loss better than −18 dB and an isolation better than −20 dB. The six-finger Lange coupler results in a −3.2+/−0.5-dB coupling bandwidth from 9.5 to 17 GHz, with a return loss and isolation better than −16 dB. The coupler using reentrant sections results in a −3.4+/−1.1-dB coupling bandwidth from 6.9 to 18.8 GHz with a return loss and isolation better than −21 dB. It is shown that CPW Lange couplers are not sensitive to planarization effects, while for the design of couplers using reentrant sections, the effect should be taken into account. The Lange couplers have the additional advantage that they are easier to design, have a lower insertion loss, and can be very well predicted using method-of-moments simulations.**

***Index Terms*—Coplanar waveguide, integrated passives, Lange coupler, quadrature coupler.**

I. Introduction

THE trend toward high-volume low-cost RF and microwave applications requires that suitable packaging techniques need to be developed. They should offer a high degree of integration to reduce size and weight, but also cost and power consumption. The multilayer thin-film multichip module technology (MCM-D) offers a very high reproducibility of very small line dimensions and is, therefore, a promising technology for the low-cost integration of RF and microwave circuits [1], [2].

The layer buildup of the used MCM-D technology is given in Fig. 1. It consists of a main Cu coplanar-waveguide (CPW) layer between two benzo-cyclobutene (BCB) layers ($\varepsilon_r = 2.7$, $\tan\delta = 5.0 \times 10^{-4}$) on a glass substrate ($\varepsilon_r = 6.2$, $\tan\delta = 9.0 \times 10^{-4}$). More information on the technology can be found in [3]. Various types of high-performance passives (spiral inductors, TaN resistors, BCB and Ta_2O_5 capacitors, etc.) can be integrated [3]–[5]. Integrating the passives directly on the MCM substrate gives a size and cost reduction and increases the packaging density.

A CPW-based technology is being used as this eliminates the need for backside wafer processing and wafer thinning, hereby also reducing cost. Through-substrate vias are not required and it is also highly compatible with flip-chip mounting of active devices or chips.

Recently, a full monolithic-microwave integrated-circuit (MMIC)-type design library offering equivalent models and auto-layout features for integrated passive devices and discontinuities has been demonstrated for thin-film MCM-D, hereby allowing a co-design between the active devices and integrated passives [2], [4]. Besides lumped elements, distributed elements, such as 3-dB quadrature couplers, are also essential elements that need to be integrated in microwave systems as they are ideal components for use in balanced amplifiers, mixers, and QPSK modulators. This will be discussed in this paper.

The realization of CPW-based quadrature couplers using two coupled lines is well known [6], [7], but a 3-dB realization generally requires very small spacings, which makes the circuit prone to processing variations.

The Lange coupler, first proposed in [8], overcomes this problem by using four strips in the same metal layer. An alternative layout was presented in [9], some design methods can be found in [10]–[12], and a six-finger version was presented in [13]. However, all the above papers deal with microstrip realizations. CPW-based Lange couplers have only recently received more attention. In [14] and [15], the classical microstrip design procedure is followed for the design of a CPW Lange coupler on a single and a multilayered substrate, respectively, while in [16], an experimental approach is being used. However, a comparison between different design methods and a discussion on the dependency of the circuit on planarization effects has not been given.

A coupler using reentrant sections can also be used to increase the coupling [17], [18] without decreasing the slots. The integration of reentrant section couplers in a low-cost MCM-D technology has, however, not been demonstrated, and the sensitivity of the design toward planarization effects has not been pointed out.

In this paper, we will discuss the design and integration of four- and six-finger CPW Lange couplers and couplers based on reentrant sections into multilayer thin-film MCM-D. Three methods for the design of CPW Lange couplers (four-

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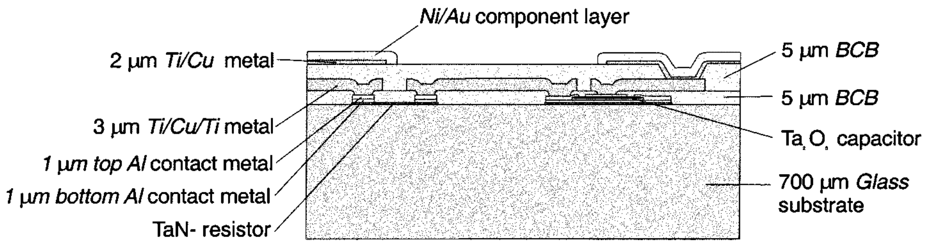


Fig. 1. Layer buildup of IMEC's MCM-D technology.

TABLE I
MEASURED VERSUS SIMULATED CHARACTERISTIC IMPEDANCE (Z_c) AND EFFECTIVE DIELECTRIC CONSTANT ($\varepsilon_{\rm eff}$) FOR DIFFERENT CPW GEOMETRIES ON MCM-D

width	slot	extracted		simulated	
μm	μm	Z_c	ε_{eff}	Z_c	ε_{eff}
16	51	114	2.85	112	2.94
27	45	96	2.90	94	2.99
44	37	78	2.93	77	3.02
55	31	70	2.94	69	3.03
66	26	63	2.94	62	3.02
77	20	56	2.93	55	3.00
86	16	50	2.92	50	2.99

and six-finger realizations) are investigated, and the results are compared with measurements. A coupler using reentrant sections is also designed and realized. Finally, all implementations are compared regarding insertion loss, sensitivity to BCB planarization effects, and ease of design.

In Section II, the quasi-TEM program, used for the analysis of the multiconductor multilayered geometries, is briefly explained and its accuracy is demonstrated. The method used to measure the quadrature couplers is also discussed. The design of the four-finger CPW Lange couplers is discussed in Section III, while the design of the six-finger CPW Lange couplers is discussed in Section IV. Couplers based on reentrant sections are finally discussed in Section V.

II. QUASI-TEM ANALYSIS AND MEASUREMENT METHOD

The multiconductor multilayered structures are analyzed using the quasi-TEM method explained in [15] and [19]. The main advantage is that the optimization of the couplers geometry can be done in a fast and efficient way. The accuracy of the method has been verified by comparing the measured and simulated line parameters of several CPW lines in our MCM-D technology (Table I). An excellent accuracy can be observed.

The measurements of the couplers were performed using Cascade wafer probes (100-μm pitch) and an HP8510 network analyzer. The system was calibrated with line-reflect-match (LRM), using the LRM impedance standard substrate (ISS) ground–signal–ground (G–S–G) alumina substrate of Cascade Microtech. The reference plane was set to 25 μm beyond the physical beginning of the line by positioning with contact marks.

After the initial calibration, an accurate equivalent model of the MCM-D contact pad is subtracted from the measurements [5].

All couplers were terminated by on-wafer 50-Ω termination resistors and the effect of the nonideal termination resistance and the load's series inductance was subsequently removed from the measurements using [20]. For this purpose, 4–6 on-wafer realizations were measured, depending upon the symmetry of the coupler. In this way, accurate measurements have been obtained.

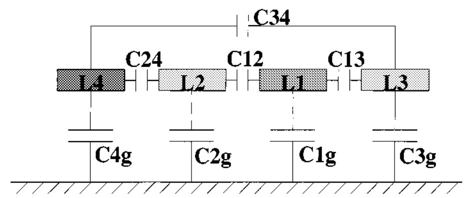


Fig. 2. Schematic representation of the capacitances involved in the design of a CPW Lange coupler.

III. FOUR-FINGER LANGE COUPLERS

A. Design Methods

In the method of Paolino [11], all capacitances in the four-conductor system (Fig. 2) are calculated. C_{23} and C_{14} are neglected, as these lines are of the same potential. The capacitances in the even and odd mode are given by

$$C_{\rm even} = C_{1g} + C_{4g} \tag{1}$$

$$C_{\rm odd} = C_{1g} + C_{4g} + 2(C_{12} + C_{13} + C_{24} + C_{34}). \tag{2}$$

By repeating this with and without dielectrics, the characteristic impedance and effective dielectric constant of the even and odd modes are obtained. For a 3-dB coupler, the dimensions are determined to obtain the required impedances $Z_{\rm even} = 120.7\ \Omega$ and $Z_{\rm odd} = 20.7\ \Omega$.

In the method of Ou [10], the required dimensions of the four-strip coupler are derived from the even- and odd-mode parameters of two coupled lines. Coupling between nonneighboring lines is neglected and the mutual coupling between all lines is assumed identical. A two-line equivalent is derived, assuming that the following relation exists between the mutual coupling (C_m) and the capacitance-to-ground of the inner ($C_{\rm in}$) and outer ($C_{\rm ex}$) lines

$$C_{\rm in} = C_{\rm ex} - (C_{\rm ex}C_m)/(C_{\rm ex} + C_m). \tag{3}$$

In the method of Kajfez *et al.* [12], coupling between nonneighboring lines is neglected and the mutual coupling between all lines is assumed identical. The capacitance-to-ground in the even mode is determined by evaluating an equivalent (single strip) transmission line, and the slot and width are given by

$$S_{\rm equivalent} = S_{\rm ground}^{\rm Lange}$$
$$W_{\rm equivalent} = 4.W_{\rm Lange} + 3.S_{\rm Lange} \tag{4}$$

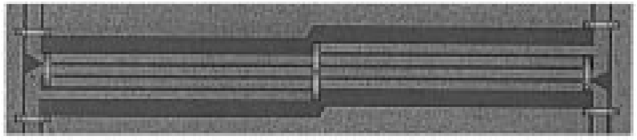


Fig. 3. Picture of a four-finger CPW Lange coupler.

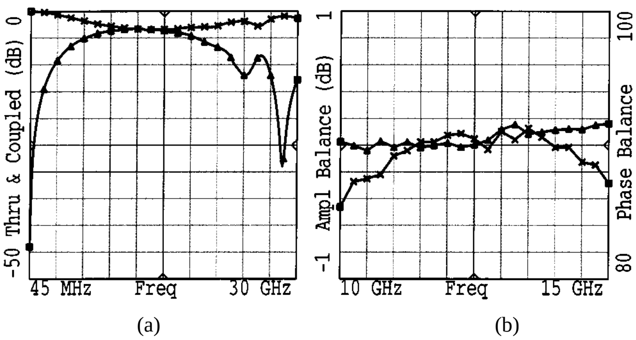


Fig. 4. (a) Thru (x) and coupled (Δ) port. (b) Amplitude (x) and phase (Δ) balance for the four-finger CPW Lange coupler designed using the method of Paolino.

where $S_{\text{ground}}^{\text{Lange}}$ is the distance between the outer strip and the ground plane in the four-conductor Lange coupler, W_{Lange} is the width of the strips, and S_{Lange} is the slot between the lines. The mutual capacitance is derived from the odd-mode impedance of a two-conductor system.

For a 2.8-dB coupler (amplitude balance of 0.4 dB), with a slot (s) of 20 μm, the method of Ou results in a strip width (w) of 41.5 μm and a slot-to-ground (s_g) of 157 μm. The method of Paolino results in $w = 56$ μm, $s_g = 123$ μm, while the method of Kajfez *et al.* results in $w = 47$ μm, $s_g = 109.5$ μm. The length of the coupler is a quarter-wavelength at the design frequency (14 GHz), being 3020 μm (the mean value of the even- and odd-mode quarter-wavelength has been taken). Losses have been neglected during calculations.

A picture of a four-finger CPW Lange coupler is given in Fig. 3. Bridges have been added to all ports to suppress the excitation of the parasitic slot-line mode when the coupler is used in a circuit.

B. Measurements

The results for the coupler designed using the method of Paolino are given in Figs. 4 and 5. We have obtained in the 10.8–14.9-GHz band a return loss better than −18 dB, an isolation better than −20 dB, an amplitude balance below 0.2 dB, and a phase balance of (90.2°±0.9°). The center frequency is, therefore, slightly lower than predicted by the quasi-TEM method.

The insertion loss of the coupler is low due to the Cu metallizations and the low-loss dielectrics and is −3.35 dB (−3 dB is due to the power split).

C. BCB Planarization

The quasi-TEM program can easily account for a change in BCB thickness. It is, however, not possible to incorporate the effect of BCB planarization, as all layers are assumed to be perfectly flat during analysis. The surface profile of the Lange coupler is depicted in Fig. 6. Here, we see that the top BCB layer is not perfectly flat, which results in a reduced BCB thickness in the slots and on the strips.

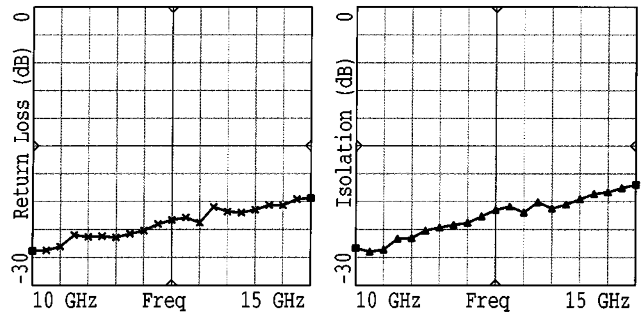


Fig. 5. Return loss (x) and isolation (Δ) for the four-finger CPW Lange coupler designed using the method of Paolino.

Fortunately, the Lange coupler is not sensitive to BCB planarization effects: when the coupler is resimulated using 4-μm-thick BCB layers, the predicted coupling (using the quasi-TEM program and the method of Paolino) increases by 0.05 dB, the matching impedance only varies slightly.

D. Design Method Comparison

Only the couplers designed using the method of Paolino and the method of Ou have been fabricated. The measured results are summarized in Table II. The coupler designed using the method of Paolino has a better performance as both return loss as isolation are superior. This behavior has also been found for other couplers, targeted at −3.2- and −3-dB coupling.

To make a comparison between the three design methods, we will now simulate (losses are neglected) the coupler, designed using the method of Paolino, with the three design methods.

The method of Paolino predicts an amplitude balance (A_{bal}) of 0.4 dB with a matching impedance (Z_m) of 50 Ω. The method of Ou predicts $A_{\text{bal}} = -0.1$ dB and $Z_m = 47$ Ω, while the method of Kajfez *et al.* predicts $A_{\text{bal}} = 0.7$ dB and $Z_m = 48$ Ω. Due to the higher concentration of the field, the losses in the odd mode are larger than the losses in the even mode. This results in a decreasing amplitude balance (expected drop of ±0.2 dB). As the measurements indicate an amplitude balance of 0.2 dB, we conclude that the method of Paolino gives the best prediction of the performance of the coupler.

The same reasoning can be done for the coupler designed using the method of Ou. The method of Paolino predicts $A_{\text{bal}} = 0.65$ dB with $Z_m = 55$ Ω. The method of Ou predicts $A_{\text{bal}} = 0.4$ dB and $Z_m = 50$ Ω while the method of Kajfez *et al.* predicts $A_{\text{bal}} = 1$ dB and $Z_m = 54$ Ω. Again, a drop of about 0.2 dB in amplitude balance can be expected due to the different losses in the even and odd modes.

We can conclude that the prediction of the couplers performance using the quasi-TEM program and the method of Paolino is very good and better than previously published results: an amplitude balance of 0 dB was targeted in [15], while the measurements indicate an amplitude balance of 0.8 dB with a return loss of −15 dB.

We can conclude that, for the same layout, the method of Paolino predicts a larger coupling than the method of Ou, which

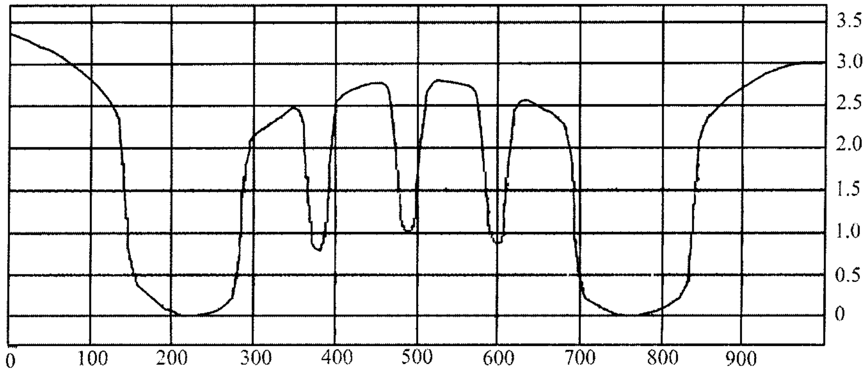
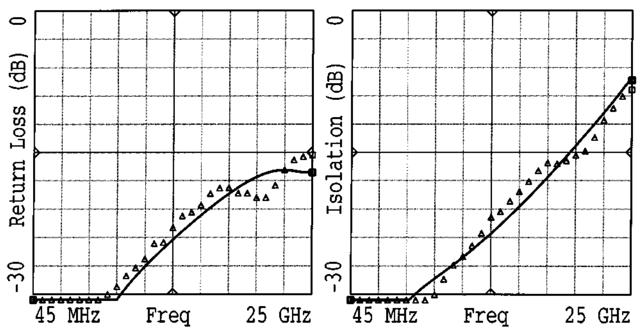


Fig. 6. Surface profile of a four-finger CPW Lange coupler. The top BCB layer is not perfectly flat due to the BCB planarization effect. Units are in micrometers.

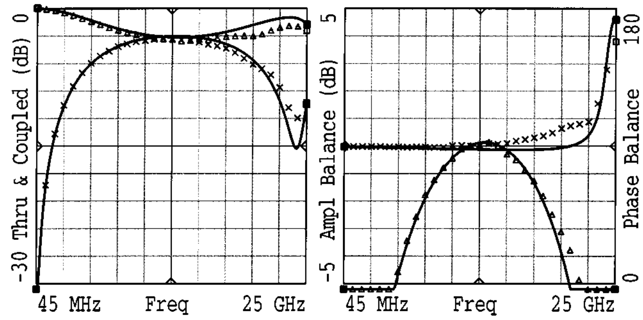
TABLE II
MEASURED RESULTS FOR THE CPW LANGE COUPLERS DESIGNED USING THE METHODS OF OU AND PAOLINO

	Paolino	Ou
Frequency band	10.8 – 14.9 GHz	10.2 - 16.3 GHz
Return loss	< -18 dB	< -15 dB
Isolation	< -20 dB	< -17 dB
Amplitude balance	< 0.15 dB	< 0.3 dB
Phase balance	90.2 +/- 0.9 deg	91.3 +/- 1.6 deg



(a) (b)

Fig. 7. MoM simulations (—) versus measurements (Δ) for the four-finger CPW Lange coupler. (a) Return loss. (b) Isolation.



(a) (b)

Fig. 8. MoM simulations (—) versus measurements for the four-finger CPW Lange coupler. (a) Thru (Δ) and coupled (x) port. (b) Amplitude (Δ) and phase (x) balance.

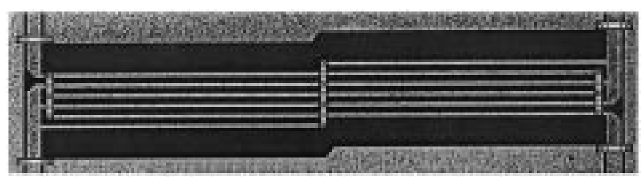


Fig. 9. Six-finger CPW Lange Coupler.

explains the difference between measured and simulated amplitude balance in [15].

E. Method-of-Moments (MoM) Results

Using the quasi-TEM program, the dimensions of the coupler can be determined in a fast and easy way. It is, however, not possible to account for the effect of the feeding lines and the strip switching in the middle of the coupled-line section. This has been done using a two-and-one-half-dimensional (2.5-D) simulator (HP-Momentum). The results are compared with measurements in Figs. 7 and 8. As the circuit is not prone to BCB planarization and the losses in the even and odd modes are low, an excellent correspondence between measured and simulated S-parameters has been obtained. The center frequency of the coupler is also predicted with very high accuracy.

IV. SIX-FINGER REALIZATIONS

A 3-dB coupler designed using the method of Paolino requires the dimensions $w = 23$ μm, $s = 35$ μm, and $s_g = 170$ μm. The length of the coupler is a quarter-wavelength at the design frequency (14 GHz), i.e., 3069 μm. The six-finger CPW Lange coupler is shown in Fig. 9. Bridges have been added to all ports to suppress the excitation of the parasitic slot-line mode when the coupler is used in a circuit.

A. Measurements

The coupler, designed using the method of Paolino, has been fabricated and measured. We have obtained in the 9.5–17-GHz band an amplitude balance below 0.5 dB, a return loss and isolation better than −16 dB, and a phase balance of (90°±2°). The results are shown in Figs. 10 and 11. A good agreement between measurement and simulation has been obtained. The insertion loss of the coupler is −3.3 dB (−3 dB is due to the power split).

The predicted performance is better than previous results: for a 1.2-dB target value, [16] achieved an amplitude balance of 1.6 dB with a return loss of −12 dB.

B. BCB Planarization

As with the four-finger Lange coupler, this coupler is also not sensitive to BCB planarization effects: when the coupler is resimulated using 4-μm-thick BCB layers, the predicted coupling

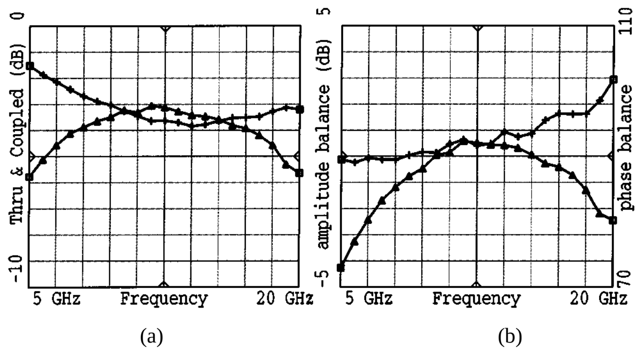


Fig. 10. (a) Measured coupled (Δ) and thru ($+$) port. (b) Measured amplitude (Δ) and phase balance ($+$) of the six-finger CPW Lange coupler.

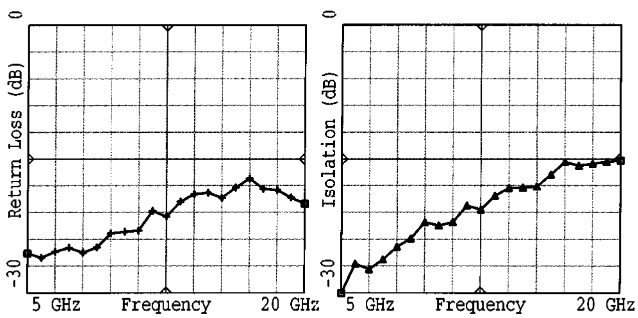


Fig. 11. Measured return loss ($+$) and isolation (Δ) of the six-finger CPW Lange coupler.

(using the quasi-TEM program and the method of Paolino) only increases by 0.05 dB, while the matching impedance only varies slightly.

C. Design Method Comparison

For the layout obtained using the method of Paolino, the method of Ou predicts $A_{\rm bal} = -0.4$ dB and $Z_m = 41\ \Omega$. This means that, for the same layout, the method of Paolino predicts a tighter coupling than the method of Ou and a higher matching impedance. The measurements indicate a tighter coupling than predicted by both methods. Therefore, the method of Paolino yields the best results.

D. MoM Results

The performance of the coupler was also predicted with a 2.5-D simulator (HP Momentum). The correspondence between the measurements and simulation is presented in Fig. 12. As the coupler is not sensitive to BCB planarization and the losses in the even and odd modes are low, an excellent agreement has been obtained. The center frequency of the coupler is also accurately predicted.

V. Couplers Using Reentrant Sections

The strips of the coupler are located on the Cu metallization, the floating potential patch is realized on the top metal level (Fig. 1). The location of the two strips was switched to get the quadrature outputs on the same side of the coupler. In one realization, this is done in the middle (leading to a more symmetric

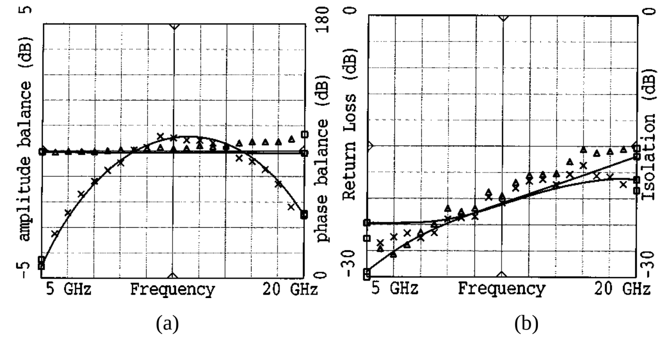


Fig. 12. (a) Measured amplitude (x) and phase balance (Δ) versus simulation ($-$). (b) Measured isolation (Δ) and return loss (x) versus simulation ($-$) of the six-finger CPW Lange coupler.

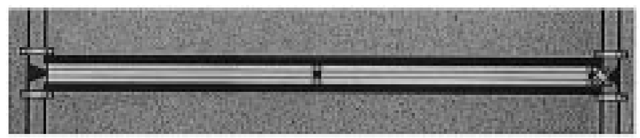


Fig. 13. Layout of a coupler using reentrant sections. The two strips are switched at the right-hand side of the coupler.

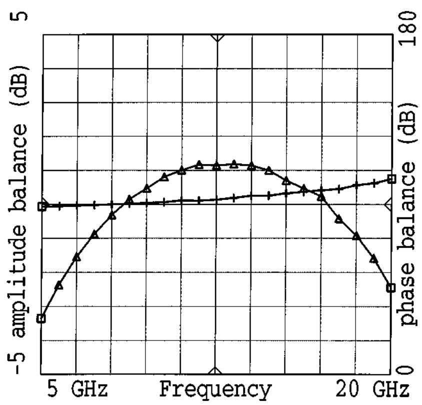


Fig. 14. Measured amplitude (Δ) and phase balance ($+$) of the coupler using reentrant sections.

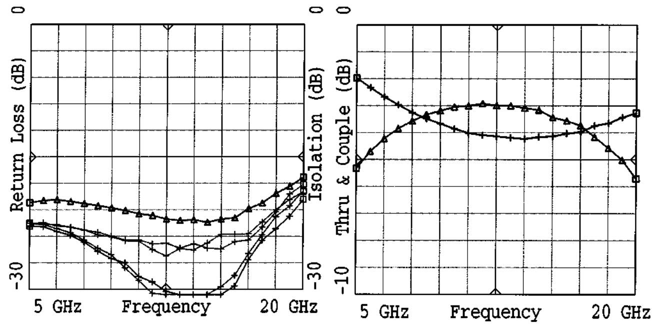
coupler), in the other realization (Fig. 13), this is done at the end of the strips (less symmetry, but the coupled lines are not disturbed in the coupling section). The measured performance of the two realizations is, however, nearly equal.

The dimensions of the coupler are $w = 38\ \mu$m, $s = 40\ \mu$m, and $s_g = 58\ \mu$m. The floating potential patch is extended 10 μm beyond the edge of the strips. The length of the coupler is a quarter-wavelength at the design frequency (14 GHz), which results in a total coupling length of 3094 μm. Bridges were added at the four ports to suppress the excitation of the parasitic slot-line mode when the coupler is used in a circuit.

A. Measurements

The measured results are given in Figs. 14 and 15. We have obtained, in a 6.9–18.8-GHz band, an amplitude balance lower than 1.1 dB, a return loss and isolation better than -21 dB, and a phase balance of (92.7°$\pm$4°).

The insertion loss of the coupler is -3.5 dB (-3 dB is due to the power split).



(a) (b)

Fig. 15. (a) Measured isolation (△) and return loss (+). (b) Measured thru (+) and coupled (△) port of the coupler using reentrant sections.

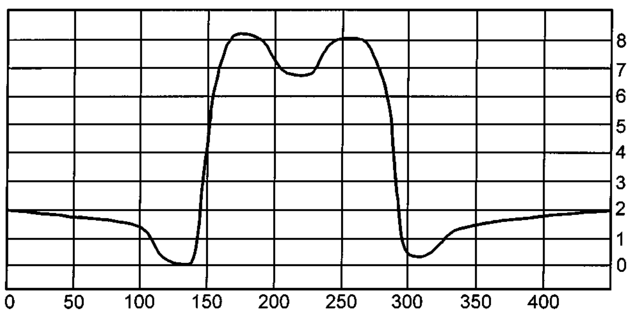


Fig. 16. Measured surface profile of the quadrature coupler using reentrant sections (units are in micrometers).

B. BCB Planarization

The effect of BCB planarization should be accounted for when designing this type of coupler. If a lossless performance and perfectly flat 5-μm-thick BCB layers are assumed, the quasi-TEM program predicts a coupling of 2.8 dB. The measurements indicate a much stronger coupling (amplitude balance of 1.1 dB). This can be mainly explained by the effect of BCB planarization.

In Fig. 16, we have depicted the measured surface profile for this coupler. Here, we notice that the assumption of the perfectly flat BCB layer is not fulfilled. The top metal, for example, shows a dip of approximately 1 μm in the middle of the coupler. Thus, in this small region, the patch is very near to the strips. The electric field is concentrated in the part where the distance between the strip and patch is minimal. Due to BCB planarization, the area under the patch is almost completely reduced to the area underneath the dip. This results in a highly confined field with increased conductor losses for the odd mode.

If we assume BCB layers with a uniform thickness of 4 μm, the quasi-TEM program predicts an amplitude balance of 1.2 dB. Due to the increased losses caused by the BCB planarization effect, the amplitude balance will drop slightly. We can, therefore, conclude that this type of coupler is very sensitive to the exact BCB thickness. The sensitivity can be reduced by putting the floating potential plate on the bottom metal. The dip in the middle of the coupler then disappears, resulting in a more uniform distance between the strips and floating potential plate.

C. MoM Results

The effect of BCB planarization cannot be very well simulated. The losses in the odd mode are quite large compared to the losses in the even mode. It is, therefore, difficult to accurately predict the performance of this coupler. When a uniform thickness of the BCB layers of 4 μm is used, an amplitude balance of 0.8 dB is obtained.

It is useful to note that when the coupling length of this coupler is reduced to 1447 μm while the lateral dimensions remain the same, we obtain, in the 23–28.7-GHz band, an amplitude balance below 0.15 dB, a return loss better than -19 dB, and an isolation better than -21.5 dB [21]. The difference in coupling between the two versions can be completely attributed to the loss in the odd mode, which increases with frequency.

VI. Architectural Comparison

The insertion loss of the Lange couplers is lower than the couplers using reentrant sections. The six-finger Lange coupler has the lowest insertion loss, but also consumes the largest area. This coupler also has a very large ground-to-ground spacing, such that its use at higher frequencies will be limited.

The CPW Lange couplers are not sensitive to BCB planarization effects. The coupler using reentrant sections has an increased sensitivity. The CPW Lange couplers are, therefore, easier to design and have an increased repeatability.

Several design methods for CPW Lange couplers have been evaluated. The method of Ou and Kajfez *et al.* have the advantage that only simulations of two coupled lines in a multilayered substrate are required. For this, the techniques in [22] and [23] can be used. The method of Paolino yields a coupler with a better performance, though requires a program that is able to calculate all capacitances in the multiconductor multilayered system. This technique has the additional advantage that the strip widths do not have to be equal and can be optimized separately. The best prediction of the Lange coupler's performance has been obtained using 2.5-D simulators. A good way to design the couplers is, therefore, to make an estimate of the couplers geometry using the quasi-TEM program with the method of Paolino, followed by a 2.5-D verification.

VII. Conclusions

The design and measurement of four- and six-finger CPW Lange couplers into thin-film MCM-D has been discussed. Several design methods for CPW Lange couplers have been evaluated for the first time. The method of Paolino consistently gives better results as compared to the method of Ou.

For the four-finger CPW Lange coupler, we have obtained, in the 10.5–14.5-GHz band, a return loss better than 20 dB, an amplitude balance below 0.2 dB, and a phase balance of ($90^\circ \pm 1^\circ$). A good agreement between measurement and simulation has been obtained. The Lange couplers are not sensitive to BCB planarization. A very accurate prediction of the couplers performance can be obtained using the MoM.

For the six-finger CPW Lange coupler, we have obtained in the 9.5–17-GHz band, an amplitude balance below 0.5 dB, a return loss and isolation better than 16 dB, and a phase balance of (90°±2°). This coupler has a large ground-to-ground spacing, which makes it more sensitive toward the presence of a ground plane underneath the glass wafer and limits the high-frequency performance.

Couplers using reentrant sections can also be integrated into MCM-D. In the 6.9–18.8-GHz band, an amplitude balance lower than 1.1 dB, a return loss and isolation better than −21 dB, and a phase balance of (92.7°±4°) has been obtained. The couplers performance can be fairly well predicted when the BCB planarization effect is taken into account. This realization has a larger insertion loss as compared to the CPW Lange coupler. The coupler has a smaller ground-to-ground spacing, which makes it less sensitive toward the presence of a ground plane underneath the glass wafer.

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