Novel Coupled-Line Conductor-Backed Coplanar and Microstrip Directional Couplers for PCB and LTCC Applications

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***Abstract*—Novel coupled-line conductor-backed coplanar and microstrip directional couplers, convenient for manufacturing in standard printed circuit board (PCB) or low-temperature co-fired ceramic (LTCC) technology, are proposed. The coplanar coupler, consisting of a layered structure with four strips and covering a −10 to −2.6 dB coupling coefficient, is theoretically ideally impedance matched and perfectly isolated at all frequencies under the assumption of validity of quasi-static approximation and two-mode propagation. The microstrip coupler, a modification of the coplanar one, can be ideally compensated only in an area of strong coupling coefficients. The novel couplers are not sensitive to lateral misalignment of conductive layers, and not sensitive to thickness and dielectric permittivity tolerances of applied dielectric substrates. Preliminary experimental results for 2.7-, 3-, and 8.34-dB couplers, designed both in PCB, as well as LTCC technology are presented.**

***Index Terms*—Asymmetric coupled lines, directional couplers, low-temperature co-fired ceramic (LTCC), multiconductor transmission lines, multilayer circuits, printed circuit board (PCB).**

I. Introduction

ADVANCES in substrate technologies and a substantial progress in computer-aided design (CAD) have led to the development of multilayer RF/microwave circuits. The integration of RF, high-speed digital, and dc power circuits in multilayered assemblies using printed circuit board (PCB) or low-temperature co-fired ceramic (LTCC) technologies has become a common practice.

PCBs lay a foundation for RF/microwave circuits and are being manufactured in unprecedented quantities in a boom period from the wireless telecommunications industry [1]. Multilayer circuits in up to a dozen or so layers, and mixed-dielectric circuits that incorporate different laminate materials in the same multilayer board, are produced. This latter capability provides circuit designers with the flexibility to mix low- and high-frequency digital and RF/microwave circuits to reduce space and manufacturing costs.

Multilayer LTCC substrates with screen-printed conductors are considered recently as a key technology for coming RF wireless communication and automotive applications [2]–[6]. They offer low-cost, high-volume, and small-size modules, which assure three-dimensional (3-D) high integration, high reliability, and the potential for buried inductors, capacitors, and resistors. Furthermore, almost all the passive components can be fabricated in one manufacturing process, and a portion of the surface area can be used for mounting active devices.

Most of PCB or LTCC multilayer RF passive devices are embedded between the dielectric layers having the same or almost the same dielectric permittivity. This way, *multilayer* coupled-line directional couplers are also realized. If they are designed in a strip-line dielectrically homogeneous configuration, high coupler's performance can be achieved. If they are placed on the top of the board using microstrip- or coplanar-type dielectrically nonhomogeneous configurations, they suffer from poor directivity. Techniques used for compensation of couplers in an inhomogeneous medium (making them quasi-ideal [7], [8]) depend on a coupler structure. Symmetrical couplers are compensated equalizing even- and odd- mode phase velocities [9]–[11]. To compensate asymmetrical couplers, two different theoretical approaches are used. In the first one, optimization of the modal parameters is applied [7], [14]. In the other, equalization of the inductive and capacitive coupling coefficients and terminating the coupled lines with the proper impedances [12], [13] assures ideal matching and perfect isolation at all frequencies under the assumption of the validity of quasi-static approximation. Conditions used in the latter approach can be written as follows:

$$k_L = k_C \tag{1}$$

and

$$Z_{Ti} = Z_i \quad i = 1, 2 \tag{2}$$

where

- k_L $= L_m/\sqrt{L_1 \cdot L_2}$, the inductive coupling coefficient;
- k_C $= C_m/\sqrt{C_1 \cdot C_2}$, the capacitive coupling coefficient;
- Z_{Ti} where $i = 1, 2$, the characteristic impedances of terminating lines;
- Z_i $= \sqrt{L_i/C_i}$, where $i = 1, 2$, the characteristic impedance of line i in the presence of line j ($j = 1, 2$, $j \neq i$);
- L_i, C_i where $i = 1, 2$, the self inductance and self-capacitance per unit length of line i in the presence of line j ($j = 1, 2$, $j \neq i$), respectively;
- L_m, C_m the mutual inductance and mutual capacitance per unit length, respectively.

Manuscript received October 13, 2002; revised January 14, 2003.

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Digital Object Identifier 10.1109/TMTT.2003.812580

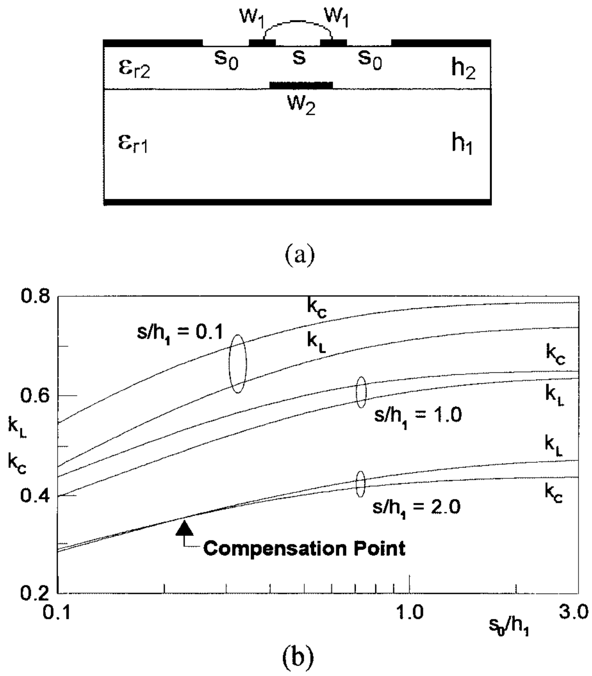


Fig. 1. (a) Cross-sectional view of broadside three-strip coupled lines. (b) Corresponding coupling coefficients for the 50-Ω matched coupler. $\varepsilon_{\mathbf{r1}} = \varepsilon_{\mathbf{r2}} = 4.2, h_2/h_1 = 0.2, t = 0$.

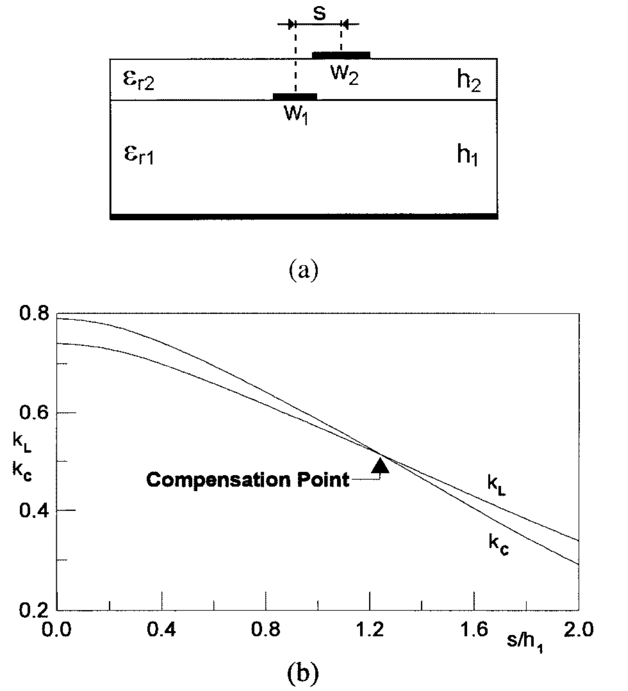


Fig. 2. (a) Cross-sectional view of offset broadside coupled microstrip lines. (b) Corresponding coupling coefficients for the 50-Ω matched coupler. $\varepsilon_{\mathbf{r1}} = \varepsilon_{\mathbf{r2}} = 4.2, h_2/h_1 = 0.2, t = 0$.

Lumped-element compensation of multilayer couplers has been recently reported [15], but it is effective in a rather narrow frequency band.

Practically none of the above-mentioned techniques can be applied to compensate a microstrip or conductor-backed coplanar-line coupler built on the top of a multilayer printed board made of the same dielectric material. Suspension of the board [10] or applying a tuning septum in the ground plane [7], [11] is not convenient from the mechanical point-of-view. To illustrate the problem, let us look into properties of two asymmetrical coupled-line structures, shown in Figs. 1(a) and 2(a). Both can be compensated using mixed dielectric media [7], [8], but—as our calculations prove—they can be compensated only in a very narrow range of structural parameters if $\varepsilon_{\mathbf{r1}} = \varepsilon_{\mathbf{r2}}$ [see Fig. 1(b)], where curves of $k_{\mathbf{L}}$ and $k_{\mathbf{C}}$ intersect for $s/h_{\mathbf{1}} = 2.0$ and $s_{\mathbf{0}}/h_{\mathbf{1}} \approx 0.22$, and Fig. 2(b), where curves of $k_{\mathbf{L}}$ and $k_{\mathbf{C}}$ intersect for $s/h_{\mathbf{1}} \approx 1.22$). The consequence is that only a very narrow range of coupling values under condition of the coupler's compensation is achievable for a given stratification of the substrates ($k_{\mathbf{L}} \approx k_{\mathbf{C}} \approx 0.35$, and $k_{\mathbf{L}} \approx k_{\mathbf{C}} \approx 0.5$ for the couplers shown in Figs. 1(a) and 2(a), respectively).

The intention of this study was to find a coupled-line structure allowing compensation in the multilayer printed board environment, having a wide range of realizable coupling coefficients, and being sensitive neither to lateral misalignment of conductive layers, nor to thickness and dielectric permittivity tolerances of applied dielectric substrates. The geometry of the proposed structures is shown in Fig. 3 [16]. The first structure, shown in Fig. 3(a), was presented at the last IEEE Microwave Theory and Techniques Society (IEEE MTT-S) International Microwave Symposium (IMS) [17]. In this paper, we expand the subject on several new calculations carried out for the first structure and propose a new microstrip version of the coupler [see Fig. 3(b)]. The structures are configured as four coupled conductor-backed coplanar lines or microstrip lines. Two external lines on the top conductive layer are bridged using planar wires at the ends of the coupled-line section and are connected to the first pair of input/output lines. The middle line is connected to the bottom one through via-holes, and connected to the second pair of input/output lines. The second pair of input/output lines reaches the top conductive layer utilizing via-hole connection. The input/output lines can be connected to the coupled-line structure in such a way that the output signals are from the same side of the coupler. This feature is important

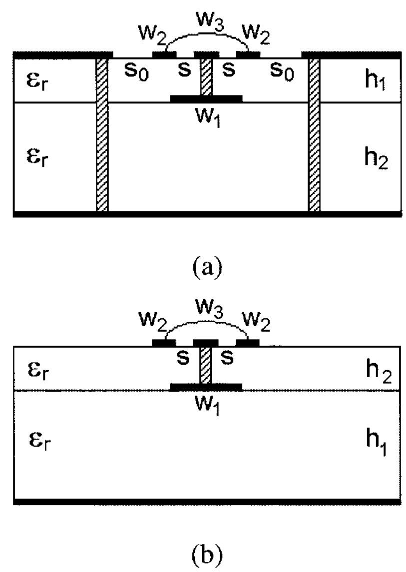


Fig. 3. Cross-sectional view of novel directional couplers in structures of: (a) conductor-backed coplanar and (b) microstrip coupled lines.

if the coupler is utilized in balanced circuits such as balanced amplifiers or mixers.

Areas of achievable coupling coefficients under the compensation conditions, tuning properties, and tolerance behavior are demonstrated in Section II, mainly for the structure shown in Fig. 3(a). The microstrip version, shown in Fig. 3(b), is also considered and comprehensively examined. Details concerning two- and four-mode coupler's analyses are also discussed. Furthermore, measured results obtained not only for the tightly and weakly coupled coplanar couplers, designed in PCB technology [17], but also for two 3-dB microstrip couplers designed in LTCC technology, are presented in Section III.

II. Analysis

In our analysis, which was performed assuming zero thickness conductors ($t = 0$) and using the quasi-static spectral-domain method [18], we calculated the geometrical dimensions of 50-Ω matched directional couplers in the structures shown in Fig. 3, and the corresponding coupling coefficients $k_{\mathbf{L}}$ and $k_{\mathbf{C}}$, aiming to fulfill the condition of $k_{\mathbf{L}} = k_{\mathbf{C}}$. These calculations were carried out for two different dielectric materials: BT-Epoxy $\varepsilon_{\mathbf{r}} = 4.2$ (PCB) and Du Pount 951 or NTK GC-11 $\varepsilon_{\mathbf{r}} = 7.8$ (LTCC), and the results corresponding to the structure shown in Fig. 3(a) are presented in Figs. 4 and 5, respectively. The structural dimensions are normalized to the thickness of the first dielectric substrate $h_{\mathbf{1}}$ and are given only for $h_{\mathbf{2}}/h_{\mathbf{1}} = 0.2$ dielectric substrates thickness ratio. It is clearly visible that the coplanar couplers for PCB and LTCC applications are compensated in the range of coupling coefficients from -10.6 to -2.6 dB and from -8.0 to -2.8 dB, respectively; let us notice the difference between $s_{\mathbf{0}}$ limits in Figs. 4 and 5. The corresponding widths of the lines and spaces between them are convenient for practical realization. They never lay below the $0.1h_{\mathbf{1}}$ limit. The assumed coupling coefficient can be realized in a variety of structural dimensions, especially in the middle region of coupling coefficients.

The physical behavior of the "tuning" process of the 50-Ω matched coupler is shown in Fig. 6. We assume *a priori* constant values for $s_{\mathbf{0}}$ and s in order to make the tuning process easier and, in this example, we choose them to achieve the tight coupling [$s_{\mathbf{0}} = 1.5h_{\mathbf{1}}$ and $s = 0.1h_{\mathbf{1}}$, see curves plotted in Fig. 4(a)]. In this way, having only three variables $w_{\mathbf{1}}$, $w_{\mathbf{2}}$, and $w_{\mathbf{3}}$ and three conditions written by (1) and (2), we give up achieving a strictly assumed coupling coefficient under the condition of compensation and we only wish to equalize the coupling coefficients $k_{\mathbf{L}}$ and $k_{\mathbf{C}}$. The point of compensation is searched altering widths of the strips $w_{\mathbf{1}}$, $w_{\mathbf{2}}$, and $w_{\mathbf{3}}$. $w_{\mathbf{1}}$ is a variable and $w_{\mathbf{2}}$ and $w_{\mathbf{3}}$ are chosen in such a way that the coupler is always impedance matched. The tuning is begun when $w_{\mathbf{1}}$ is small. The coupling coefficients $k_{\mathbf{L}}$ and $k_{\mathbf{C}}$ are then different, and the corresponding isolation of the coupler is low [see Fig. 6(b)]. With the increase of $w_{\mathbf{1}}$, the difference between the coupling coefficients slowly diminishes. At the point where $w_{\mathbf{1}}$ achieves maximum of its normalized value of approximately 0.86 (for higher values of $w_{\mathbf{1}}$ characteristic impedance $Z_{\mathbf{1}}$ of line 1 is then always lower than 50 Ω), $k_{\mathbf{L}}$ is above point O and $k_{\mathbf{C}}$ is above point P, and they are still different. Diminishing

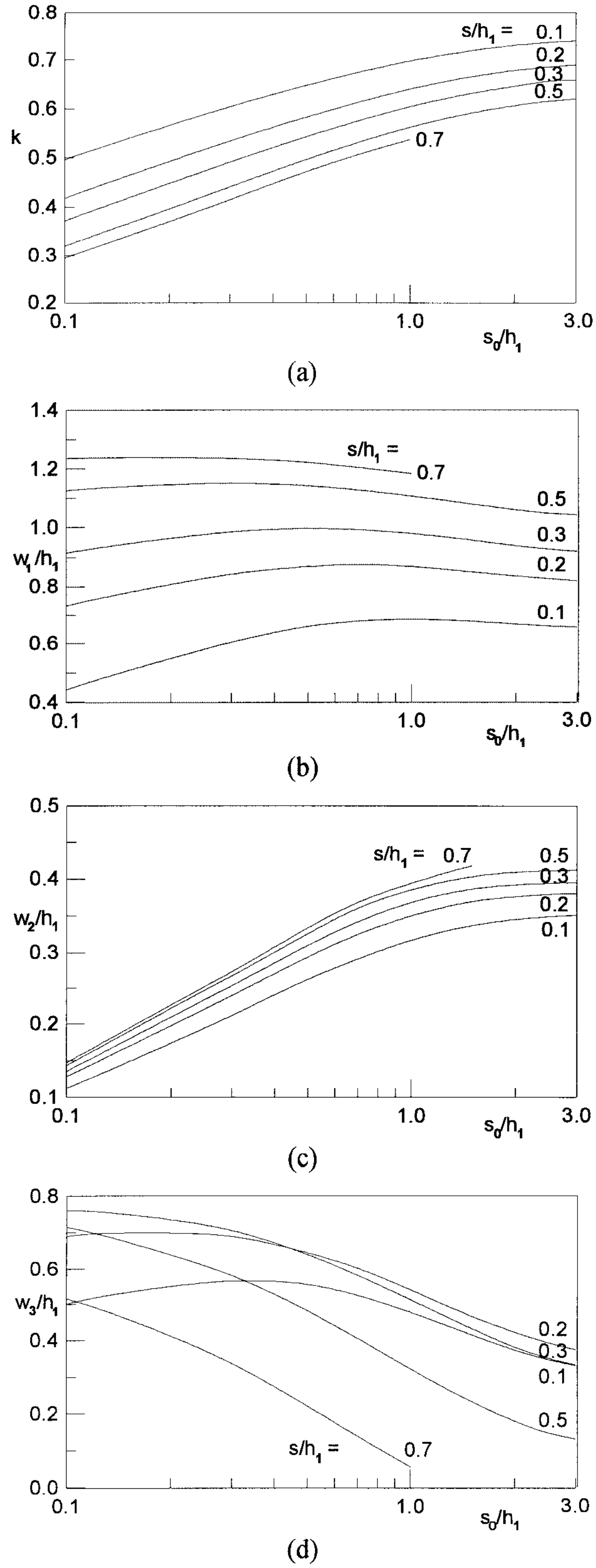


Fig. 4. (a) $k = k_{\mathrm{L}} = k_{\mathbf{C}}$, (b) $w_{\mathbf{1}}/h_{\mathbf{1}}$, (c) $w_{\mathbf{2}}/h_{\mathbf{1}}$, and (d) $w_{\mathbf{3}}/h_{\mathbf{1}}$ versus $s_{\mathbf{0}}/h_{\mathbf{1}}$ and $s/h_{\mathbf{1}}$ as a parameter for the compensated coupler made in BT-Epoxy; $\varepsilon_{\mathbf{r}} = 4.2, h_{\mathbf{2}}/h_{\mathbf{1}} = 0.2, t = 0$, the coupler's structure —Fig. 3(a).

widths of all the strips the coupler is finally compensated at point K. Corresponding isolation is very high. Let us remark that there is no equalization of coupling coefficients at point O, in which $k_{\mathbf{L}}$ reaches either point O or M, and $k_{\mathbf{C}}$ reaches point

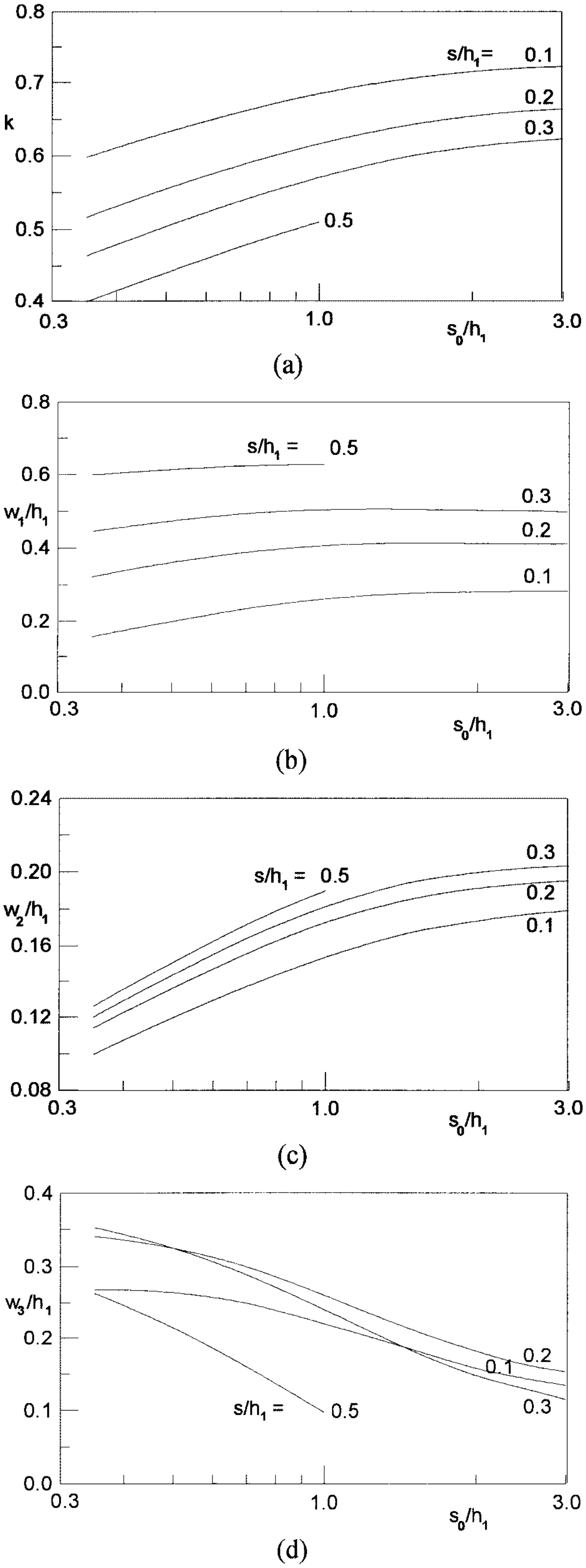


Fig. 5. (a) $k = k_L = k_C$, (b) w_1/h_1, (c) w_2/h_1, and (d) w_3/h_1 versus s_0/h_1 and s/h_1 as a parameter for the compensated coupler made in LTCC; $\varepsilon_r = 7.8, h_2/h_1 = 0.2, t = 0$, the coupler's structure—Fig. 3(a).

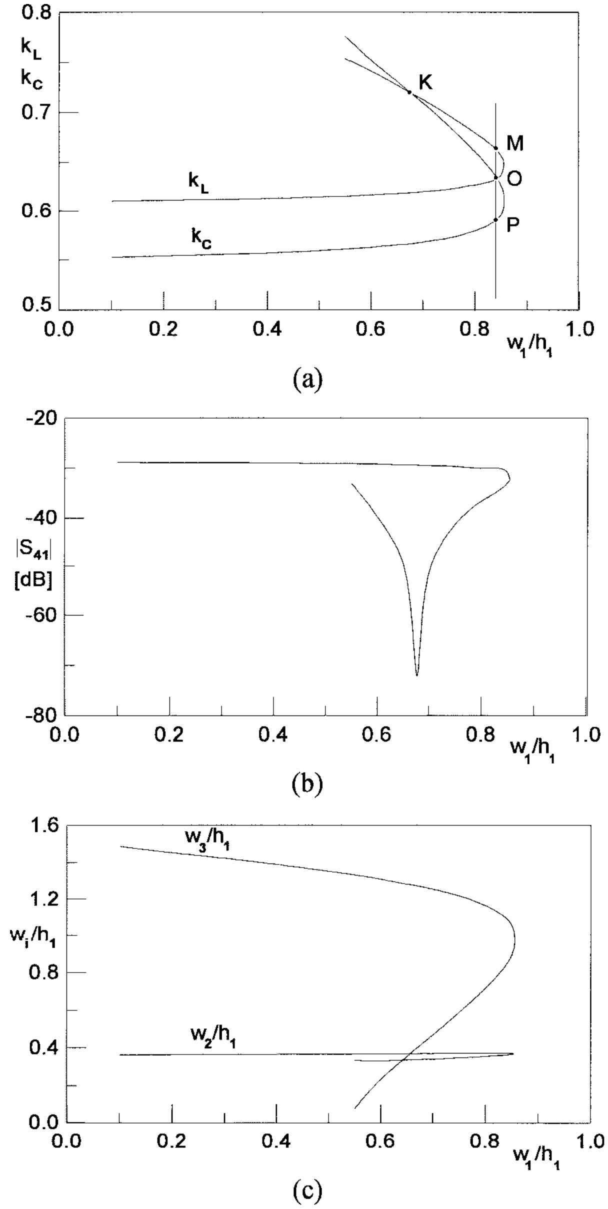


Fig. 6. Tuning process. (a) Coupling coefficients, (b) isolation, and (c) corresponding w_2/h_1 and w_3/h_1 versus w_1/h_1; $\varepsilon_r = 4.2, h_2/h_1 = 0.2, s_0/h_1 = 1.5, s/h_1 = 0.1, t = 0$, the coupler's structure—Fig. 3(a).

P or O. Plotted in Fig. 6 curves of k_L, k_C [in Fig. 6(a)] and w_2 and w_3 [in Fig. 6(c)] result from the solution of two equations ($Z_{Ti} = Z_i$, $i = 1, 2$), where the independent variable is w_1/h_1 and the dependent variables are w_2/h_1 and w_3/h_1. For small values of w_1, when influence of the strip w_1 on behavior of the coupled-line structure is small, there is only the one solution. Let us notice that, in this area of w_1, k_L, k_C, and S_{41} are almost constant and that only w_3 decreases substantially when w_1 increases (to keep constant 50-Ω characteristic impedance Z_1). From a particular value of $w_1/h_1 \approx 0.55$ in each plot of Fig. 6, there are two branches. This is the reason why out of two points O and K, in which curves of k_L and k_C intersect, we reject the first, and only the second is the one we were looking for. The following conclusion can be drawn from the behavior of curves plotted in Fig. 6. It is better to begin the tuning process of a coupler in the proposed structure [shown in Fig. 3(a) or (b)] taking rather —as a starting point—dimensions w_1 and w_2 established for a small value of w_3, than dimensions w_2 and w_3 established for a small value of w_1. Slowly increasing w_3 and

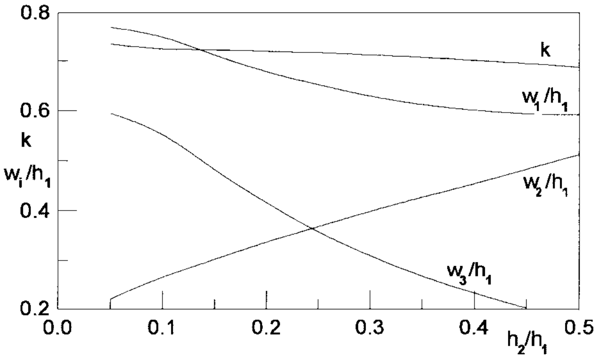


Fig. 7. Coupling coefficient k and corresponding linewidths versus normalized thickness of the second dielectric substrate h_2/h_1 for the compensated coupler; $\varepsilon_r = 4.2$, $s_0/h_1 = 1.5$, $s/h_1 = 0.1$, $t = 0$, the coupler's structure—Fig. 3(a).

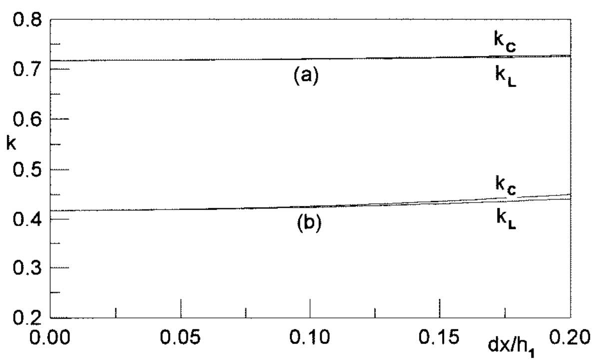


Fig. 8. Effect of lateral misalignment of conductive layers on coupling coefficients. (a) A case of tight coupling. $s_0/h_1 = 1.50$, $s/h_1 = 0.15$, $w_1/h_1 = 0.643$, $w_2/h_1 = 0.328$, $w_3/h_1 = 0.282$. (b) A case of weak coupling. $s_0/h_1 = 0.30$, $s/h_1 = 0.70$, $w_1/h_1 = 1.138$, $w_2/h_1 = 0.236$, $w_3/h_1 = 0.260$; $\varepsilon_r = 4.2$, $h_2/h_1 = 0.2$, $t/h_1 = 0.018$. The coupler's structure—Fig. 3(a).

altering widths of the strips w_1 and w_2 in order to keep 50-Ω impedance matching, one can then reach the point of compensation in a considerably shorter time because the number of iterations needed is thus much lower.

One feature of the new structure distinguishes it from other known structures of broadside-type coupled lines. Since strips w_1 and w_3 are connected through via-holes, the structure is not sensitive on composition of the board. This is illustrated by curves plotted in Fig. 7, showing that tight coupling can be realized in a wide range of thickness h_2.

The novel structure is not sensitive to lateral misalignment of conductive layers. Present day printed circuit fabrication techniques give typical layer-to-layer alignment ranges $+/-0.13$ mm [19]. Computations have shown that coupling coefficient changes from -2.89 to -2.78 dB for tightly coupled coupler, and from -7.58 to -7.03 dB for weakly coupled coupler, with very small de-compensation (see Fig. 8), and the couplers mismatch to $\mathrm{VSWR} = 1.04$ over $dx/h_1 = 0.2$ of layer-to-layer misalignment. The computations have also proven that the novel coplanar coupled-line structure is not sensitive to variation of dielectric permittivity. The coupling coefficient is almost constant and the impedances vary by $+/-1$ Ω within the range of ε_r from 4.0 to 4.4, for any coupling level.

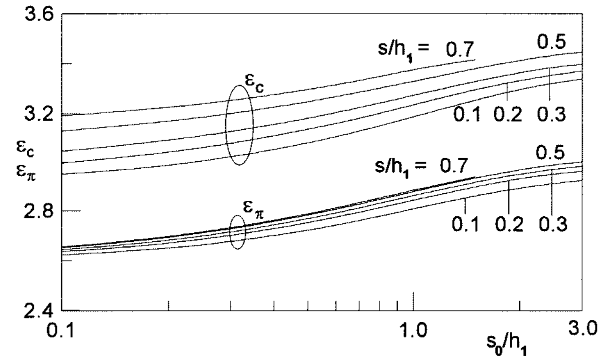


Fig. 9. Effective dielectric constants for the two modes propagated in the compensated structure of Fig. 3(a) versus s_0/h_1 and s/h_1 as a parameter. $\varepsilon_r = 4.2$, $h_2/h_1 = 0.2$, $t = 0$.

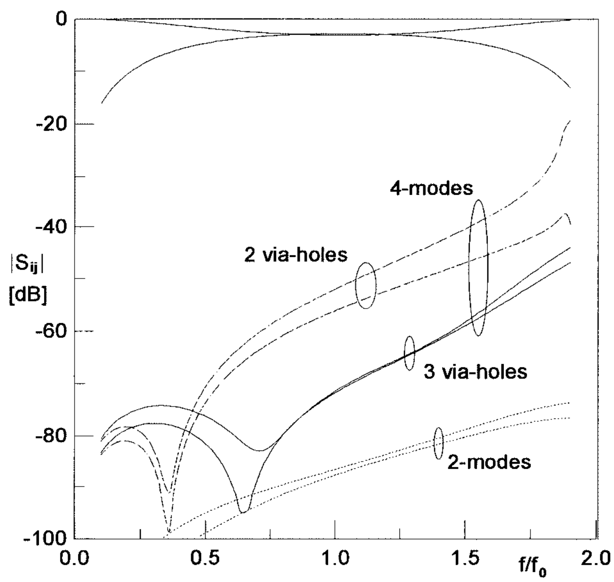


Fig. 10. Frequency-dependent characteristics of the directional coupler shown in Fig. 3(a) as a result of two- and four-mode analyses. $\varepsilon_r = 4.2$, $h_2/h_1 = 0.2$, $s_0/h_1 = 1.5$, $s/h_1 = 0.1$, $w_1/h_1 = 0.677$, $w_2/h_1 = 0.337$, $w_3/h_1 = 0.415$, $t = 0$.

So far presented computations have been carried out assuming two-orthogonal-mode propagation. This assumption is valid if strips w_1 and w_3, as well as two external strips w_2 are perfectly connected along the whole length of the coupled lines. Since the structure belongs to the class of asymmetric coupled transmission lines, these two modes always propagate with different velocities [12], [13]. Examples of curves of effective dielectric constants for the modes are plotted in Fig. 9. A correcting length of 50-Ω transmission line should be added to the proper ports of the coupler to assure constant frequency-independent 90° phase difference between the signals at the transmission and coupled ports [20], [7]. Comparison of frequency-dependent characteristics of the coupler, computed as results of the coupler's simplified two-mode and exact four-mode analyses, is shown in Fig. 10. It is clearly seen that the higher the number of via-holes connecting w_1 and w_3 strips, the higher the return loss and isolation of the coupler. The use of only two via-holes at the ends of the coupled-line section may result in deterioration of the coupler's performance.

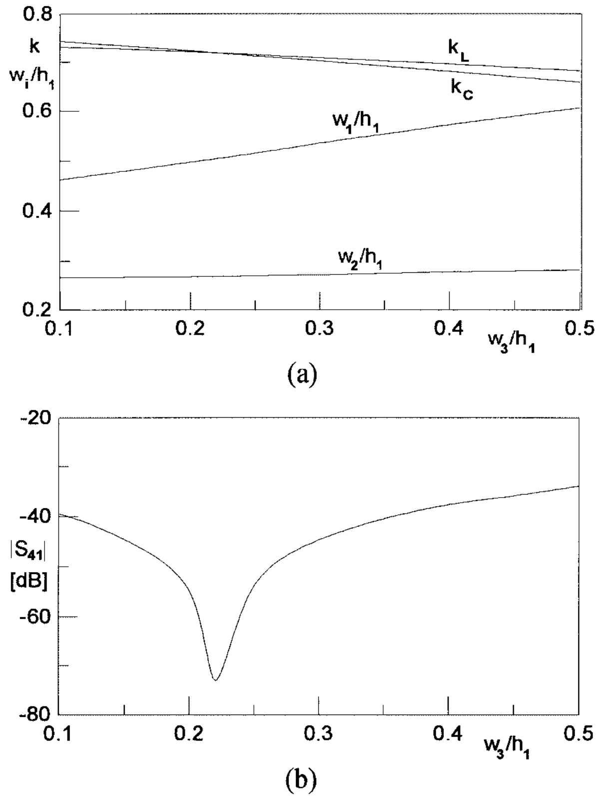


Fig. 11. (a) k_L and k_C, w_1/h_1 and w_2/h_1, and (b) isolation for the 50-Ω matched coupler shown in Fig. 3(b) versus w_3/h_1; $\varepsilon_r = 5.7, h_2/h_1 = 0.2, s/h_1 = 0.13, t = 0$.

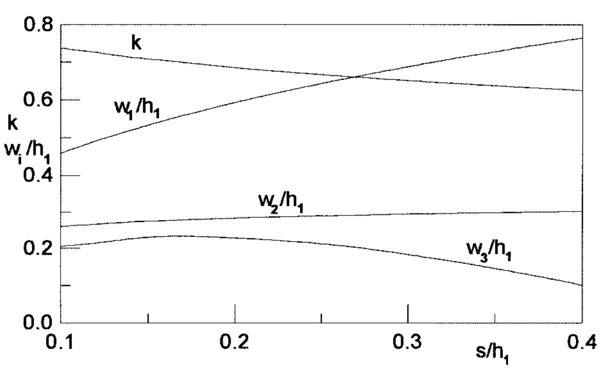


Fig. 12. Area of coupling coefficients available for the compensated microstrip version of the novel structure and corresponding strip widths. $\varepsilon_r = 5.7, h_2/h_1 = 0.2, t = 0$.

TABLE I
STRUCTURAL PARAMETERS FOR DESIGNED COUPLERS. DIMENSIONS IN MILLIMETERS

#	Fig.	ε_r	h_1	h_2	s_0	s	w_1	w_2	w_3	t	k (dB)
1	3a	3.58	1.47	0.25	2.29	0.18	1.17	0.53	0.66	0.017	-2.70
2	3a	3.58	1.47	0.25	0.25	0.90	2.01	0.30	0.93	0.017	-8.34
3*	3b	7.8	1.00	0.20	-	0.13	0.28	0.18	0.10	0.010	-2.95
4	3b	5.7	1.00	0.20	-	0.18	0.49	0.26	0.12	0.010	-2.95

* #3 coupler is not fully compensated ($k_L = 0.718$, $k_C = 0.707$), because of w_3 limit.

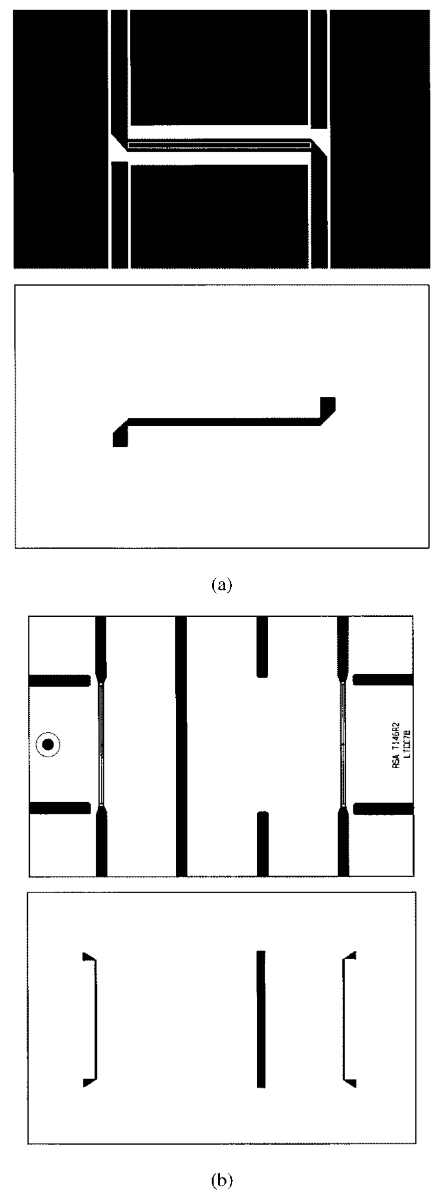
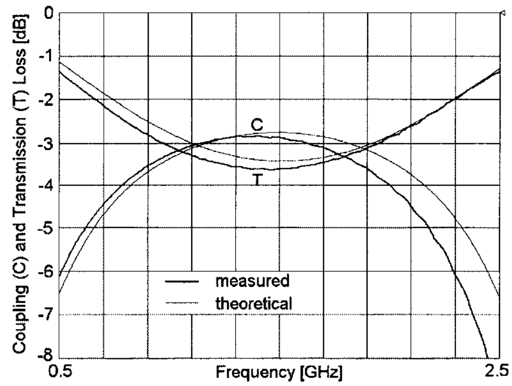


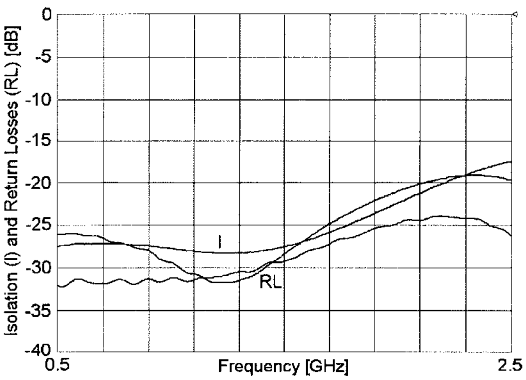
Fig. 13. Layouts of: (a) 2.7-dB coupler (#1, Table I) made using Arlon 25FR laminates and (b) LTCC test board with two 3-dB couplers (#3, Table I) and two 50-Ω transmission lines made using NTK GC-11 tape.

The microstrip version of novel coupled lines is shown in Fig. 3(b). The compensation possibilities of this structure have been verified for tight couplings [$s_0 \rightarrow \infty$ for the structure of Fig. 3(a)]. The results are presented in Figs. 11 and 12. For the assumed value of $s/h_1 = 0.13$, compensation is achieved for a specified width relation between strips w_1 and w_3 (from Fig. 11(b), $w_3/h_1 \approx 0.22$, where the isolation achieves the highest value, and from Fig. 11(a), corresponding $w_1/h_1 = 0.5$, which gives $w_3/w_1 \approx 0.44$). Compensation in this structure is possible only in the limited range of structural parameters (see Fig. 12, where w_3 reaches $0.1h_1$ geometrical limit for 4.0-dB coupling). The microstrip version of coupled lines has small lateral dimensions so that very compact meander-shaped space-saving 3-dB couplers can be designed.

The quasi-static analysis presented in this section has shown many attractive properties of the new coupler structures. Results

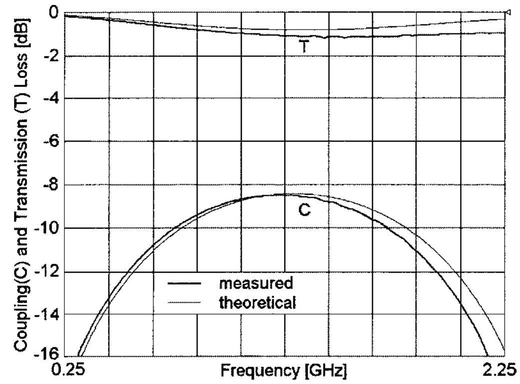


(a)

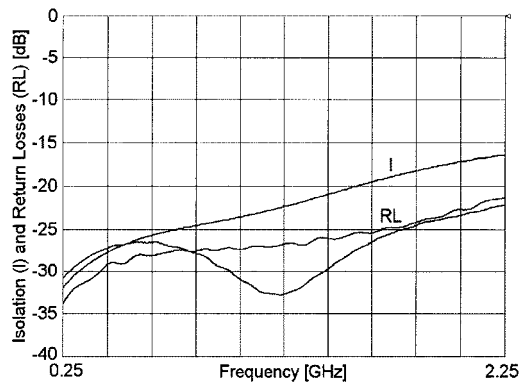


(b)

Fig. 14. Characteristics of the 2.7-dB coupler (#1, Table I). (a) Calculated and measured coupling and transmission loss. (b) Measured isolation and return losses (the theoretical ones are greater than 39 dB).



(a)



(b)

Fig. 15. Characteristics of the 8.34-dB coupler (#2, Table I). (a) Calculated and measured coupling and transmission loss. (b) Measured isolation and return losses (the theoretical ones are greater than 43 dB).

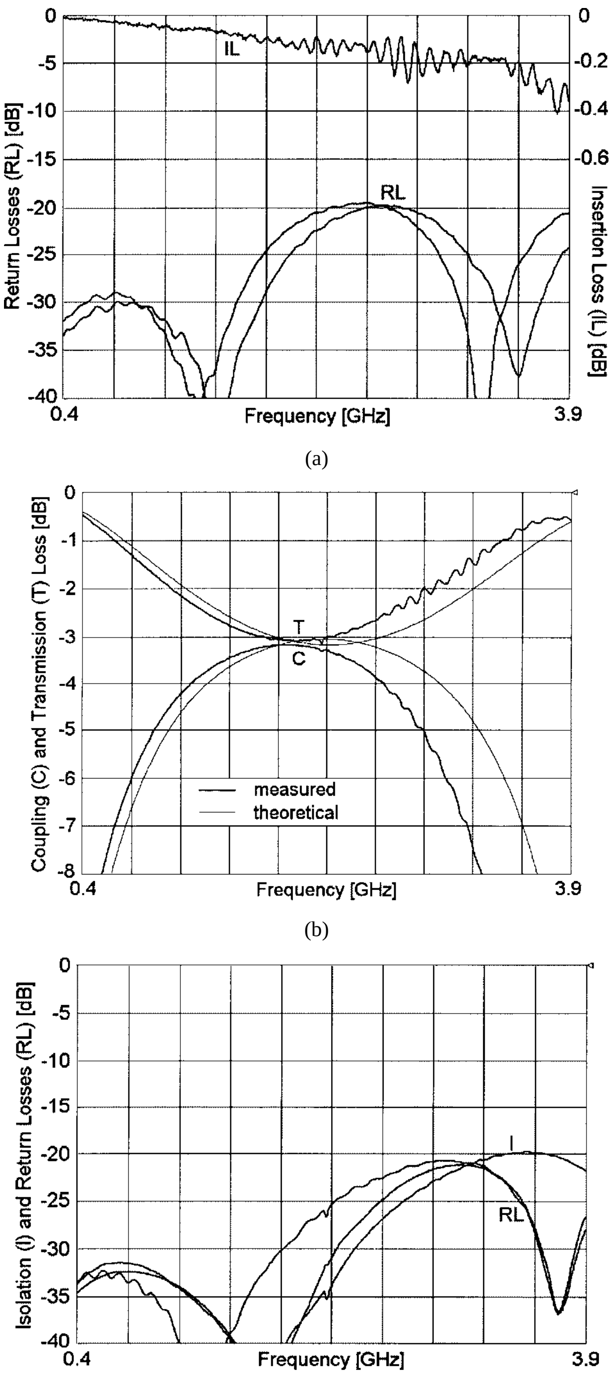
of this analysis can be used as a very good starting point for full-wave and 3-D analyses, where frequency dispersion of the coupled-line parameters and discontinuities effects can be taken into account. Nevertheless, exemplary 2.7, 3, and 8.34-dB couplers have been preliminary designed in PCB and LTCC technologies using only results of the quasi-static analysis. They have been manufactured and the measured results are presented in Section III.

III. Examples of Design and Experimental Results

The structural parameters and coupling coefficients for the lines that form four exemplary coplanar and microstrip couplers are given in Table I. Two of those couplers (#1 and #2 in Table I) have been designed as 2.7-dB (#1) and 8.34-dB (#2) coplanar couplers using Arlon 25FR laminate and manufactured in PCB technology. Let us notice that both of them are built using laminates of the same thickness. The third and the fourth, both of 2.95-dB coupling, utilize NTK GC-11 and NOC-1 LTCC tapes, respectively. They have been manufactured in LTCC technology. The thickness of the metallization t was taken into consideration in the design using LINPAR software [21].

Layouts of 2.7-dB coupler and LTCC NTK GC-11 tape test board with two 3-dB couplers and sections of single 50-Ω transmission lines are shown in Fig. 13. Measured and calculated responses of the couplers, listed in Table I as #1–#3, are presented in Figs. 14–16, respectively. At the center frequency, the measured coupling of the 2.7-dB coupler is equal to 2.87 dB, and its return loss and isolation are greater than 27 dB (see Fig. 14). The 8.34-dB coupler has coupling equal to 8.51 dB, and its return loss and isolation are greater than 22 dB at the center frequency (see Fig. 15). Better results, shown in Fig. 16, have been obtained for the LTCC coupler. The return losses and isolation follow return loss of a path: SMA-connector, 50-Ω transmission line (without or with the transition through the second conductive layer), and SMA-connector. This means that the coupler itself is well impedance matched and has high isolation. The center frequency is shifted approximately 10% down with respect to the designed one of 2.15 GHz. The return losses and isolation are greater than 20 dB in the octave frequency band. Better performance of the LTCC coupler arises from better via-hole connections in the structure. These connections have been designed as blind ones, contrary to through–ground-vias applied in PCB couplers designs. The other LTCC coupler, made using NOC-1 tape (#4 in Table I), has been also manufactured and tested. At the center frequency of 1.85 GHz, its measured coupling, transmission loss, isolation, and return losses are equal to 3.0, 3.2, 30.9, and 29.2 dB, respectively.

Here, let us notice a very good agreement between values of coupling and transmission loss calculated and measured at the center frequency for all the couplers. Isolation and return losses calculated for couplers #1–#3 in the frequency range of measurements are greater than 39, 43, and 36 dB, respectively. It is necessary to remember that the theoretical characteristics have been calculated using the quasi-static method of analysis, in which we neglect all the discontinuity problems and assume



(a)

(b)

(c)

Fig. 16. (a) Measured response of a path: SMA-connector, 50-Ω line section (without and with the transition through the second conductive layer), and SMA-connector. (b) and (c) Characteristics of LTCC 3-dB coupler (#3, Table I). The isolation and return losses calculated in the frequency range of measurements are greater than 36 dB.

that only a section of four-conductor transmission line with dielectric and metal losses, modeled using unit inductance, capacitance, resistance, and conductance matrix parameters [21], constitutes the coupler. Taking into account a strong influence of connectors and transitions on measured return losses and isolation of the coupler, we state a good agreement between the measurements and theory, especially for the tightly coupled couplers.

IV. Conclusion

The investigated new structures of directional couplers seem to be very promising for PCB and LTCC applications, where the dielectric substrates of the same dielectric permittivity compose the board. Configurations of the couplers are convenient to be realized in standard PCB or LTCC technology. The conductor-backed coplanar coupler covers -10 to -2.6 dB coupling coefficient (for $h_2/h_1 = 0.2$), being always compensated, and is not sensitive to variations of technological parameters—lateral misalignment of conductive layers, tolerances of dielectric constant, and thickness of the dielectric substrates. Compensation of tightly coupled lines can be also achieved in the microstrip version of the proposed structure for a specified width relation between strips w_1 and w_3, making it suitable for compact meander-shaped space-saving 3-dB couplers design.

The measured results for the 2.7-, 3-, and 8.34-dB couplers, manufactured in PCB and LTCC technologies, show that design upon quasi-static two-dimensional (2-D) analysis can be a very good base for further development using full-wave and 3-D field solvers.

The novel structures are compatible with different broadside coupled-line structures, presented, for instance, in [7], [8], [14], and [22]. Connection of these structures allows design of multisection couplers or broad-band baluns, where sections of compensated coupled lines of a different coupling level are necessary.

The following are a few open subjects worthy of consideration in future investigations.

1) What is the behavior of the novel structures if a mixed dielectric environment is used?
2) How different can dielectric constants be of the substrates so that it is still possible to compensate the coupler?
3) Is it possible to compensate the pure coplanar version of the structure without the ground at the bottom plane?

Acknowledgment

The authors are very grateful to E. Szulc, Ericsson AB, Stockholm, Sweden, for careful layout drawings, to Dr. H. Medelius, Ericsson AB, for help to find LTCC manufacturer, and to S. Tamada, NTK Technical Ceramics, Ratingen, Germany, for conducting the manufacturing process of the LTCC couplers.

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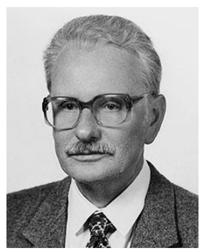

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