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HIGH PERFORMANCE 1.8-18 GHz 10-dB LOW TEMPERATURE CO-FIRED CERAMIC DIRECTIONAL COUPLER

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Abstract—This paper presents a six-section multi-layer asymmetric 10 dB directional coupler based on offset broadside coupled striplines, using Low Temperature Co-fired Ceramic (LTCC) technology, which operates over a decade bandwidth from 1.8 to 18 GHz. It features high performance transitions between the external signal layer and the buried signal layers, as well as a novel mixed first section to solve the limitations of the coupler access bends. A prototype was manufactured that exhibits a return loss of better than 15 dB, isolation of better than 23 dB and a high coupling accuracy of 10.3±0.6 dB over the 1.8–18 GHz band. This design outperforms previously reported results in terms of bandwidth and shows excellent potential for microwave measurement applications.

1. INTRODUCTION

Weakly coupled broadband directional couplers are key components of many microwave measurement systems. They are used in reflectometer setups, power meters, source leveling, automatic gain control loops, network analysis and test systems. Most common planar coupled lines built on single layer substrates, such as microstrip

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or coplanar waveguides, are quasi-TEM lines. In these cases, the even and odd modes have unequal phase velocities. This is a great disadvantage when these coupled lines are used to implement wide-band directional couplers at microwave frequencies [1, Chap. 7, 2]. Buried homogeneous structures support TEM modes with the same phase velocity, so that they are particularly well suited for the design of directional couplers. The greatest difficulties in making directional couplers in buried technologies involve: i) choosing a suitable multilayer stack and ii) designing the transitions between external signal layers and buried signal layers to achieve high performance over the complete operational bandwidth. One of the most important technologies aimed at overcomimg these difficulties is LTCC multilayer technology. Multilayer LTCC technology with screen-printed conductors is considered as a key technology for RF wireless communications [3]. It features size reduction and a high level of integration, simplifying the integration between multilayer directional couplers and surface-mount circuitry, such as the switches, amplifiers, etc., which are required in measurement systems.

In measurement applications, where phase characteristics are irrelevant, asymmetric multisection coupled-line directional couplers are an interesting alternative, as they are easy to design and offer greater bandwidth and frequency response flatness than symmetric ones for the same number of sections. In addition, the coupler's size and insertion losses are reduced by half while maintaining the same level of performance. When designing these couplers, three main difficulties arise: i) achieving tight coupling, ii) compensating for the parasitics of the discontinuities between coupler sections and the connection of coupled and signal lines, and iii) in the specific case of asymmetric couplers, separating the access ports of the tightly coupled section at one of the coupler's end, to avoid section overcoupling. Tight coupling can be achieved by using broadside coupled lines on thin substrates. This approach was used in [4, 5] and is also used in this work. On the other hand, several different alternatives have been proposed for the issue of discontinuity parasitics compensation. In [6, 7], discontinuity parasitics were modeled for offset broadside coupled stripline directional couplers and compensated for by shunt capacitances. This theory was applied in [4, 7] to design offset broadband asymmetric three-section directional couplers, but these couplers operate below 6 GHz, where discontinuity parasitics are easier to compensate for. In [5], a three-section multilayer LTCC stripline coupler was designed, using a reentrant cross section to achieve precise coupling values. In this design, stepped transitions are used to reduce parasitics between coupler sections. However, to the best of the authors' knowledge, no contributions have thus far addressed the third problem: that is, how to extract the output ports from the tightly coupled section of the coupler without degrading its performance.

This paper presents, a multisection multilayer LTCC asymmetric 10 dB directional coupler, with offset broadside coupled striplines, which operates from 1.8 to 18 GHz. It uses the high performance transitions between the external signal layer and the buried signal layers designed in [8]. Additionally, it includes a novel mixed first section, which combines Shielded Multilayer Coplanar Waveguide (SMCPW) coupled lines and offset broadside coupled striplines to extract the output ports from the tightly coupled section of the coupler, avoiding section overcoupling and thereby maintaining coupler performance. Measurements show that this design offers high coupling accuracy and excellent performance in terms of return loss and isolation, which are critical parameters for microwave measurement applications.

2. DESIGN

An asymmetric multisection equal-ripple directional coupler is a circuit in which coupling decreases gradually from the first section to the last. Each section is designed to be a quarter wavelength at the central frequency, with a pair of even-odd mode impedances, which can be found in tables in [9]. This paper presents the design, construction and measurement of a six-section asymmetric directional coupler implemented using LTCC technology, with a target passband ripple of ± 0.3 dB in the 1.8–18 GHz frequency range. Its 3D view is shown in Fig. 1. For the coupler's design and construction, a Ferro A6M substrate with $\epsilon_r = 5.9$ was used. Offset broadside coupled striplines were chosen as elemental sections because they can maintain equalized phase velocity modes and achieve the tight coupling which is needed in the first section. A cross-sectional view of the offset broadside coupled striplines and the multilayer stack chosen for the coupler design are shown in Fig. 2.

The goal of the design is to achieve high coupling accuracy around 10 dB while maintaining good performance in terms of return loss and isolation. Once the multilayer stack has been chosen, the design methodology is as follows: first, a preliminary design is made for the directional coupler body, without coupler access bends; second, the problem of extracting the output ports from the most tightly coupled section of the coupler must be addressed; and finally, the vertical transitions between external and buried signal layers must be designed.

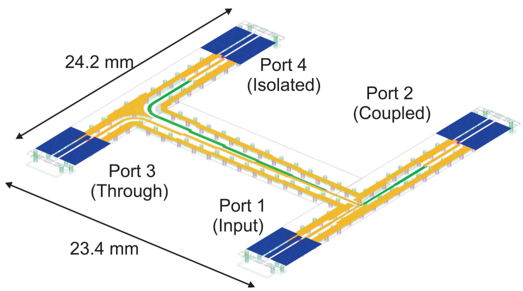

Figure 1. 3D view of the six-section asymmetric directional coupler implemented on Ferro A6M LTCC substrate.

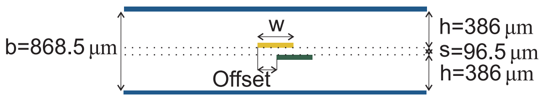

Figure 2. Offset broadside coupled striplines cross-sectional view in the multilayer stack chosen for the coupler design. Thicker substrate layers are made by joining two substrate layers of 193 µm.

Table 1. Characteristic impedances and physical dimensions of the asymmetric six-section directional coupler.

Section	$Z_{0e}(\Omega)$	$Z_{0o}(\Omega)$	W (µm)	Offset (µm)	L (mm)
1	87.72	28.5	190.5	127.0	3.09
2	74.10	33.74	228.6	256.5	3.09
3	64.79	38.59	259.0	383.5	3.09
4	58.52	42.72	269.2	525.8	3.09
5	54.44	45.93	277.0	708.7	3.09
6	51.92	48.16	282.0	947.4	3.09

2.1. Directional Coupler Body Design

The equations given in [10] are used to find the initial cross-sectional dimensions of the coupler body that implement the required even and odd impedances (Z_{0e}, Z_{0o}) listed in Table 1. These initial cross-sectional dimensions are then adjusted by circuit simulation. Then, the coupler body is simulated by 2D electromagnetic analysis using ADS Momentum, which shows nearly the same frequency response as in the circuit simulation. The coupler's dimensions are shown in Table 1.

2.2. Design of Access Ports to the Tightly Coupled Section

Once the main body of the coupler has been designed, input and output ports to the first and last sections of the coupler must be provided. At the last (weakly coupled) section, the gap between coupled lines is large enough so that access ports can be provided by simple swept bends in stripline technology [2, Chap. 4], without appreciable coupler performance degradation. However, at the first (tightly coupled) section, the separation between the coupled lines is so small that it is impossible to access these lines without causing further undesired coupling. The obvious solution for reducing section overcoupling involves using 90° mitered bends, as shown in Fig. 3. However, as will be shown later, a simulation of this circuit shows that this solution leads to greater degradation in coupler performance due to section overcoupling. This detrimental effect cannot be removed, even if the tightly coupled section length and miter factor are optimized for best performance.

Figure 3. Top view of directional couplers with access stripline ports. Swept bends and 90° mitered bends are used at the weakly and tightly coupled sections, respectively.

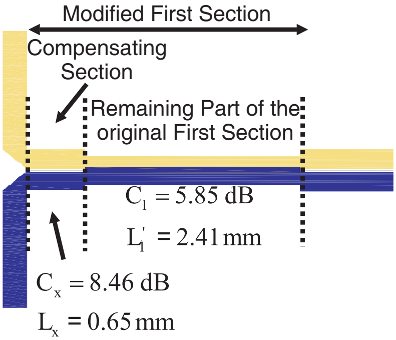

Figure 4. Top view of the modified first section including a short weakly coupled compensating section (C_x, L_x) and the remaining part of the original first section (C_1, L'_1).

In a first attempt to overcome this problem, a short weakly-coupled compensating section was included in order to reduce the total coupling in the first section, thereby compensating for the overcoupling caused by the mitered bends. Fig. 4 shows a detail of this proposal, which included a compensating section (with coupling C_x and length L_x), and the length of the first section was consequently reduced to a value L'_1, which is approximately equal to $L_1 - L_x$.

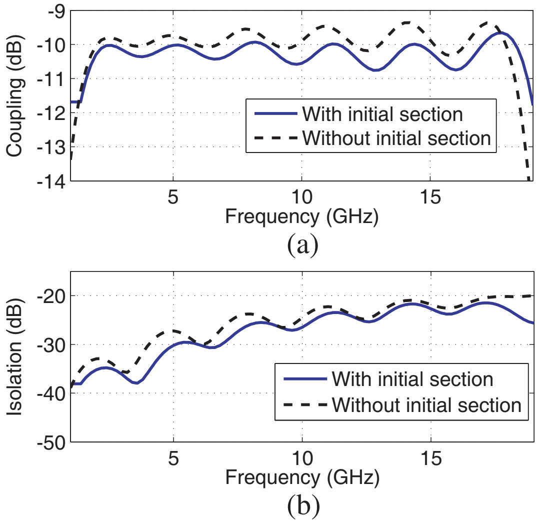

Figure 5. Simulated performance of the directional coupler with the short weakly-coupled compensating section and without it. (a) Coupling. (b) Isolation.

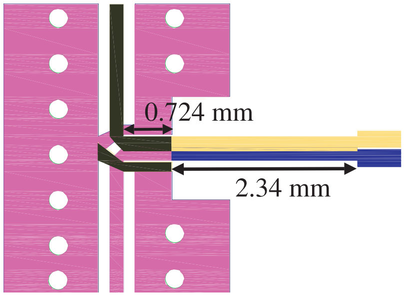

Figure 6. Top view of the novel mixed first section with SMCPW mitered bends.

After careful optimization, the best performance was obtained for the following values, $C_x = 8.24\,\mathrm{dB}$, $L_x = 0.65\,\mathrm{mm}$ and $L_1' = 2.41\,\mathrm{mm}$. To show the improvement of this technique, Fig. 5 shows the comparison in performance of both designs: the original design of Fig. 3 and the optimized one in which the first section was substituted by the optimized one in Fig. 4. It can be seen that, although this technique makes a slight improvement on the coupling parameter, it only gives a very small improvement in the coupler's isolation, which is only around 22 dB at the upper end of the band.

To solve this problem, a novel topology based on a mixed first section, composed of SMCPW coupled lines and offset broadside coupled striplines, is proposed. This novel first section is depicted in Fig. 6 and a cross-section of the SMCPW coupled lines is shown in Fig. 7. SMCPW coupled lines achieve weaker coupling than offset broadside coupled striplines for the same length and strip width, and above all, ground planes of SMCPW bends increase the shielding between them. Thus, by designing 90° mitered bends with SMCPW, and modifying the first stripline section as a combination of SMCPW coupled lines and offset broadside coupled striplines, the overcoupling problem is completely solved.

The design methodology that optimizes this technique is as follows: first, SMCPW coupled lines are designed with the same strip width and offset as the first stripline section (included in Table 1) and with a gap of 150 µm (the minimum gap available in this technology). Second, SMCPW access bends are designed for each port to have a characteristic impedance of 50 Ω. Finally, the lengths of the mixed first section are adjusted to achieve the desired coupling accuracy.

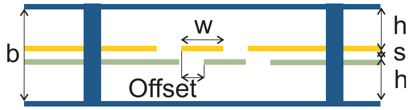

Figure 7. Cross-sectional view of SMCPW coupled lines.

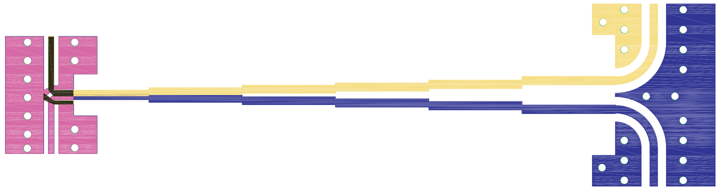

Figure 8. Top view of directional couplers with the novel mixed first section and SMCPW bends.

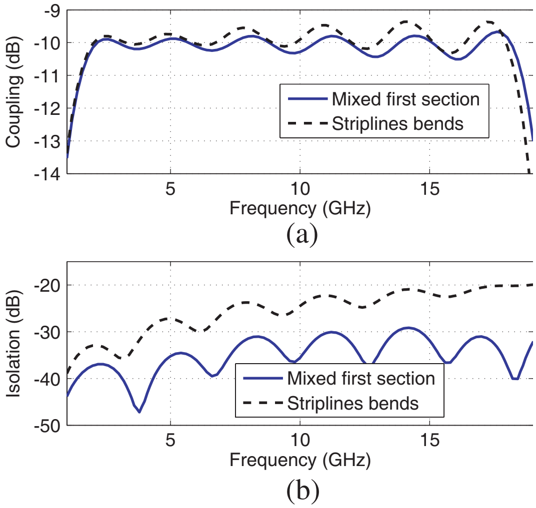

Figure 9. Simulated performance of the directional coupler with stripline bends and the directional coupler with SMCPW bends and the novel mixed first section. (a) Coupling. (b) Isolation.

In this case, the optimized lengths are $L_{\text{SMCPW}} = 0.724\,\text{mm}$ and $L_{\text{Stripline}} = 2.34\,\text{mm}$, respectively. The directional coupler with the novel mixed first section and SMCPW bends is shown in Fig. 8.

In order to demonstrate how this novel mixed first section reduces degradation in coupler performance caused by stripline bends, a full comparative analysis was carried out. Simulations were performed with the couplers shown in Figs. 3 and 8, by 2D electromagnetic analysis, and the results are depicted in Fig. 9. The overcoupling caused by stripline bends increases the coupling level up to 9.4 dB, and above all degrades the isolation, as shown in Fig. 9(b). The proposed novel first section not only keeps coupling steady, but clearly improves the isolation, keeping it better than 29 dB from DC to 19 GHz.

2.3. Design of Vertical Transitions

Once the directional coupler body has been designed and the problem of tightly coupled section access ports has been solved, the last step is to design the vertical transitions between external and buried signal layers. These transitions are crucial for the overall directional coupler performance. As shown in the previous section, at each of the four directional coupler ports, the position in the multilayer stack or the width of the buried signal line is different. Since for measurement purposes all ports have to be accessed from the same side of the board, a different transition is required for each port. These transitions have been designed to make use of intermediate transitions between the grounded coplanar waveguide (GCPW) and SMCPW to gain access to the different buried signal lines in the stack, as shown in Fig. 10. The design is based on the following basic rules:

- Every transmission line must have ground planes in the same metallization level as the adjacent lines.
- Every ground plane must be connected together.
- Signal vias must not cross any of the ground planes.

When these simple guidelines are followed, experience shows that most parasitics are avoided, the complexity of the line dimensioning problem is minimized and good performance can be achieved from DC to 20 GHz. In order to achieve these conditions, the proposed basic transition shown in Fig. 11 is divided into two sections:

- The first section, labeled section A, consists of a transition between the external GCPW and a SMCPW, both of which have a characteristic impedance of 50 Ω. In this section, the signal lines at both layers are connected with a signal via hole with a catch pad.
- The second section, labeled section B, is a transition between the SMCPW and a stripline. In this section, the SMCPW gap width is simply increased to transform the SMCPW into a stripline. To maintain the characteristic impedande, the signal line width is also slightly increased, but the difference is too small to be perceptible in Fig. 11.

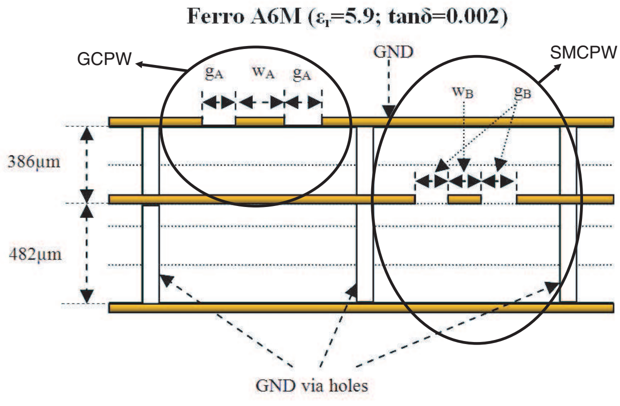

Figure 10. Transversal geometry of the LTCC stack with an external GCPW, a SMCPW and their ground planes interconnected with via holes.

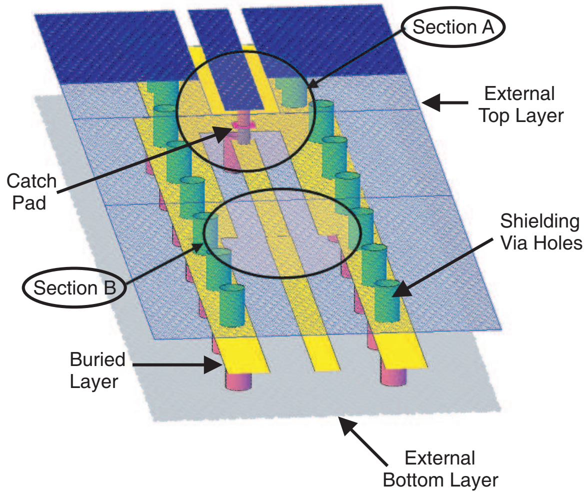

Figure 11. 3D view of the transition between GCPW and stripline. This transition is divided into two sections. Section A, from GCPW to SMCPW; and Section B, from SMCPW to stripline. Part of the upper ground plane metallization is displayed as semi-transparent to show the inner conductor's structure.

Table 2. Final dimensions of the basic transition.

ω_A (µm)	g_A (µm)	ω_B (µm)	g_B (µm)	D_{via} (µm)	L_B (mm)
399	152.6	249	292	127	3.4

Once the topology is known, the design of this transition is quite simple. First, the transversal dimensions of the different lines must be calculated to be matched to the system characteristic impedance (50 Ω in this case). In the second step, the length of the SMCPW (L_B) must be selected to avoid the coupling between high order evanescent modes generated in the discontinuities. Finally, the only parameter that must be optimized by 3D electromagnetic simulation to get the best performance from DC to 20 GHz is the signal via hole diameter. In this case, EMPIRE XCcel 3D simulation tool has been used to perform 3D electromagnetic simulations. Final dimensions of this basic transition are included in Table 2.

This basic transition was implemented in a back-to-back configuration and measured with a two-port Vector Network Analyser (VNA), using a probe station for on-wafer measurements and a TRL calibration technique. As shown in Fig. 12, there exists good agreement

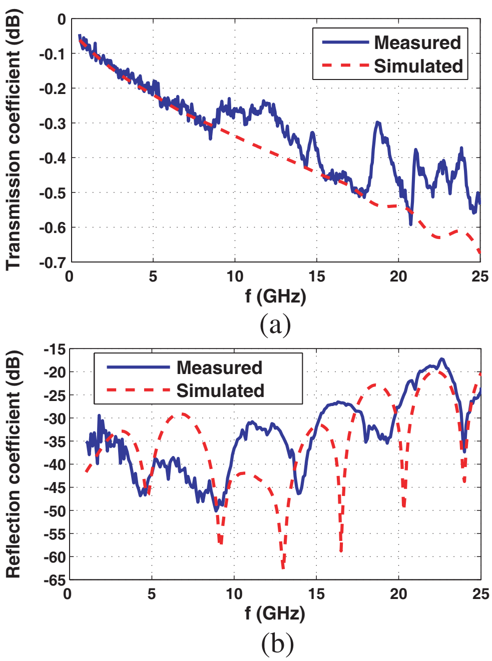

Figure 12. Simulated and measured performance of the basic transition. (a) Transmission coefficient. (b) Reflection coefficient.

between simulated and measured results. The measured transmission coefficient is better than 0.6 dB and the measured reflection coefficient is better than −26 dB up to 20 GHz.

The other required transitions were designed based on this basic transition, but including additional sections to get access to each port from the same side of the board. Similar results were also obtained for these transitions.

3. CIRCUIT CONSTRUCTION AND MEASUREMENT

To verify coupler performance, a prototype was manufactured by the Institute of Mobile and Satellite Communication Techniques (IMST GmbH). In order to achieve a good repeatability in the coupler performance a high level of precision and accuracy in strip alignment and definition is required. Thus, a very controlled process of coupled lines screen-printing on both sides of the central substrate layer was used. This process achieves a tolerance in the strip alignment and definition below 25 μm.

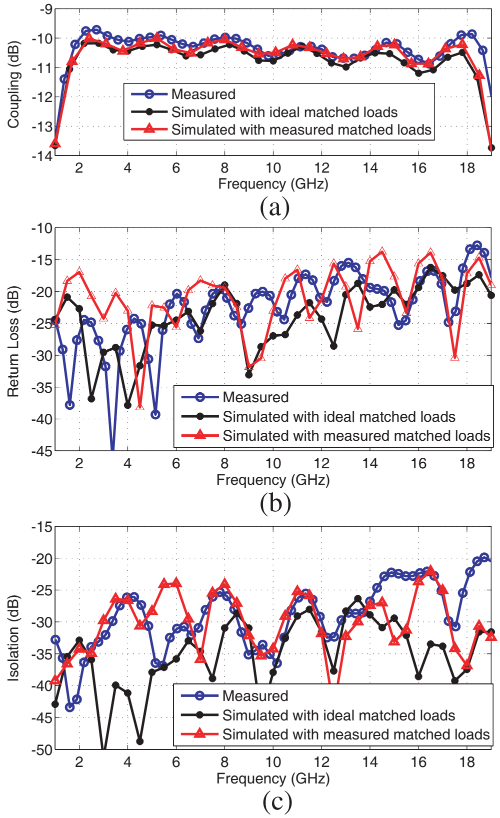

Figure 13. Simulated and measured performance of the entire 10 dB LTCC six-section directional coupler. (a) Coupling. (b) Return loss. (c) Isolation.

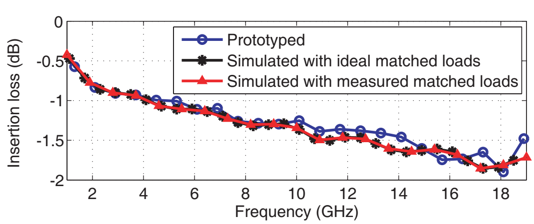

Figure 14. Simulated and prototyped insertion losses of the entire 10 dB LTCC six-section directional coupler.

The directional coupler was measured with a two-port VNA using a probe station and a TRL calibration technique. Unused ports of the coupler were loaded with matched loads consisting of two shunted 100 Ω screen-printed resistors. They were made in the top layer of the LTCC module and connected to directional coupler ports through wirebonding. Some of these matched loads were measured showing poor performance that partially degraded the measured coupler performance. Figs. 13 and 14 show the measured results, as well as a comparison of simulation results with ideal matched loads and simulation results with measured matched loads. One can see that the agreement between simulated and measured results is reasonably high. Furthermore, agreement is significantly improved when the actual loads are included in the simulations. In Fig. 13(a), one can see that the measured coupling is 10.3 ± 0.6 dB from 1.5 to 18.8 GHz, yielding a 12.5 : 1 operation bandwidth. Figs. 13(b) and 13(c) show a measured return loss of better than 15 dB and an isolation of better than 23 dB from 1 to 18 GHz. When the imperfectly matched loads are included in the simulation, an adequate level of agreement with the measurements is obtained. Thus, it is reasonable to state that intrinsic coupler parameters are approximately as follows: a coupling level of 10.6 ± 0.5 dB, an isolation of 27 dB and a return loss of 17 dB from 1.8 to 18 GHz, as shown in simulated results with ideal matched loads. Finally, a prototyped insertion loss of lower than 2 dB, very similar to simulated results, is depicted in Fig. 14. These results confirm that the proposed mixed first section is a very compelling option to avoid overcoupling at the tightest coupled section in asymmetric couplers.

4. CONCLUSION

In this paper a six-section LTCC asymmetric 10 dB directional coupler that operates from 1.8 to 18 GHz has been presented. The circuit makes use of high performance vertical transitions between GCPW and SMCPW for buried signal layers access, and a novel mixed first section to solve the problem of overcoupling caused by coupler access ports. The coupler has been manufactured by IMST GmbH, exhibiting a measured coupling accuracy of 10.3 ± 0.6 dB from 1.5 to 18.8 GHz, return loss of better than 15 dB and an isolation of better than 23 dB from 1 to 18 GHz. Therefore, the proposed directional coupler represents an effective option for microwave measurement applications, such as reflectometer setups, power meters, source leveling, automatic gain control loops, network analysis and test systems, where size reduction and low insertion losses are crucial.

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