Frequenz
62 (2008)
9–10

A Multilayer Ultra-Wideband Directional Coupler

Mario Leib, Dennis Mack, Felix Thurow and Wolfgang Menzel

Abstract – In this contribution, the well-known vertically installed planar coupler is introduced briefly, and an improved assembly technique is proposed increasing the mechanical stability of the coupler. Then, the design of a novel multilayer planar, ultra-wideband, five-sectional 3 dB directional coupler with an easier fabrication process and lower height is presented. In this approach, the necessary tight coupling at the center section for the desired ultra-broadband behavior is achieved with a multilayer configuration instead of a vertically installed substrate. The manufactured multilayer coupler has a coupling and insertion loss of 3.4 dB $\pm$ 1.1 dB and an isolation and return loss of better than 14 dB in the operating bandwidth between 3.1–10.6 GHz. The design procedure, identical for both coupler types, needs no time-consuming full-wave analysis and will be described in detail for the novel multilayer coupler.

Index Terms – Microstrip directional couplers, ultra-wideband, multilayer, planar

1. Introduction

Directional couplers are core components for many microwave systems, subsystems and measurement devices. Since the Federal Communications Commission (FCC) released a generic admission for ultra-wideband systems between 3.1 GHz and 10.6 GHz in 2002 [1], a lot of communication and radar systems for different applications are under investigation [2]. Directional couplers are of general interest for power division and combination, duplexers and beam-forming networks for array antennas. In addition to the required ultra-wide operational bandwidth, planar realizations, e. g. in microstrip technique, are desired for an easy integration and low cost of production.

A well-known and established method to realize a planar broadband coupler is the use of multiple sections of TEM coupled microstrip lines [3]. A common problem is the necessary tight coupling at the inner sections which is difficult to obtain with a standard PCB fabrication process. Several approaches exist to overcome this problem. So a tandem configuration [4], [5] or a re-entrant coupler type [6], [7] are possible solutions. The first method requires undesired wire crossovers, and the latter one occupies much more substrate area as two couplers with a reduced coupling are combined. In [8] a multilayer structure with a single slot coupling is proposed. The broadband behavior is achieved there due to the elliptical shape of the slot. An even better ultra-wideband performance with a high isolation is possible, when multiple coupling sections are applied [9]. However, the general structure is difficult to integrate, because the microstrip feeding lines are positioned on both sides of the multilayer substrate.

Another way to obtain a tight coupling is to use a vertically installed planar (VIP) hybrid [10]. In the following section this approach and its drawbacks will be presented briefly. Afterwards, the design of a novel multilayer, ultra-wideband, five-sectional 3 dB directional coupler will be shown leading to a more compact, robust and easily producible realization compared to the VIP coupler.

2. Multisectional VIP coupler

In the VIP coupler, a thin substrate with metallization on both sides is added perpendicular to the main substrate with coupled lines. Therewith, a medium coupling can be obtained (see Fig. 1, left). An even higher coupling can be achieved removing the sideways mircostrip lines and reducing the ground plane area (cf. Fig. 1, right). For stabilization purposes and equalization of the modal phase velocities, additional dielectric blocks can be put at the sides of the vertical substrate. In [11] a five-sectional ultra-wideband directional coupler is realized in such a way with a relative bandwidth of 160 %. The disadvantage of this structure is the necessary manual attachment of the vertical substrate and the fixing by soldering which is a difficult and time-consuming fabrication process. Furthermore, the vertically installed substrate is very sensitive to mechanical forces and therefore quite fragile. In order to stabilize the overall structure, a slot can be milled in the base substrate leading to a significant stability improvement and, furthermore, the mounting of the vertical substrate is eased. The electrical performance of a coupler is not affected by this as demonstrated by a realized coupler operating at 3.1–10.6 GHz (see Fig. 2).

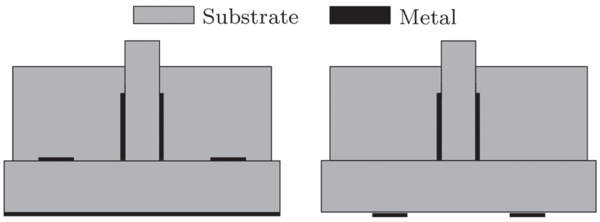

Fig. 1: Cross section of the VIP coupler for medium (left) and tight (right) coupling [11].

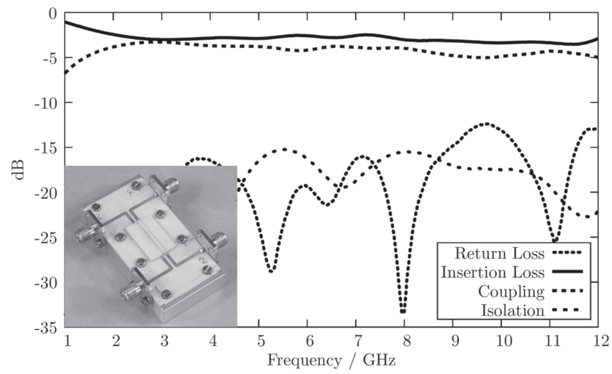

Fig. 2: Measured S-parameters for a five-sectional ultra-wideband VIP coupler (realization see inset).

However, the milling leads to another fabrication step. Therefore, a modified version of this coupler is proposed. Instead of a vertical installed substrate, the high coupling sections are rotated by 90° resulting in a simple multilayer configuration with an additional height reduction and a robust overall structure. This multilayer structure and the general

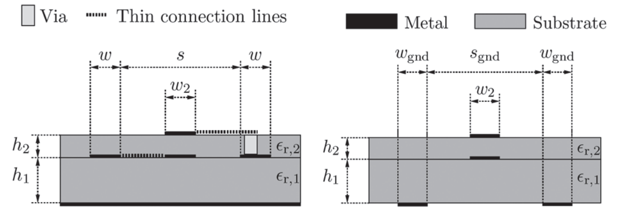

Fig. 3: Cross sections of the novel multilayer coupler (left: section type *A*, right: section type *B*).

design procedure will be described in detail in the following section.

3. Novel Multilayer Coupler Design

3.1 General Design Procedure

The concept of the broadband couplers is based on multiple sections of coupled microstrip lines. The sections are usually symmetric regarding the middle section. Each section has a length of $\lambda/4$ and can be described by the even- and odd-mode characteristic impedance ($Z_{0,\text{even}}$, $Z_{0,\text{odd}}$). In [12] tables with values for $Z_{0,\text{even}}$ and $Z_{0,\text{odd}}$ are provided for different bandwidths and ripples in order to design a specific coupler. The characteristic values for coupled microstrip lines can be determined easily with circuit simulators like e. g. [13]. For a wide bandwidth a high coupling is mandatory and leads to line distances, which are impossible to realize in microstrip technique. Instead of implementing an additional coupling using a perpendicular installed substrate like in the VIP hybrid, two multilayer section types are proposed and are shown in Fig. 3.

Both section types consist of two substrates and three metal layers and their structure was chosen to allow for cascading. Section type *A* has two transmission lines in the center separated by the top substrate and, additionally, a transmission line at each side. Both inner transmission lines are connected to one of the outer transmission lines by the help of thin lines located at the center and the edges along the line. Vias are needed at one side to get a connection to the top side of the second substrate. For the design the degrees of freedom are the parameters w, s, w_2, and h_2. In section type *B* the outer transmission lines are removed and the ground area is reduced to two ground lines in order to achieve a tight coupling. Adjustable parameters in section type *B* are the width w_{gnd} and distance s_{gnd} of the ground lines and the width of the top lines w_2.

The characteristic impedances for both modes are calculated by an EM simulation software [14]. Therewith, the characteristic impedance Z_0 and the coupling value c can be obtained for the sections by the following equations:

$$Z_0 = \sqrt{Z_{0,\,\text{even}} \cdot Z_{0,\,\text{odd}}}, \tag{1}$$

$$c|_{\text{dB}} = -20 \cdot \lg \frac{(Z_{0,\text{even}}/Z_{0,\text{odd}}) - 1}{(Z_{0,\text{even}}/Z_{0,\text{odd}}) + 1}. \tag{2}$$

In Fig. 4 and Fig. 5 typical values for different design parameters are shown for section type *A* and section type *B*, respectively. There, the same substrate material (RO4003C with $h_1 = 0.5$ mm and $h_2 = 0.2$ mm) is used to obtain similar phase velocities for both modes of section type *A*. Finally, the physical dimensions of each section for given coupler values can be read out from these diagrams.

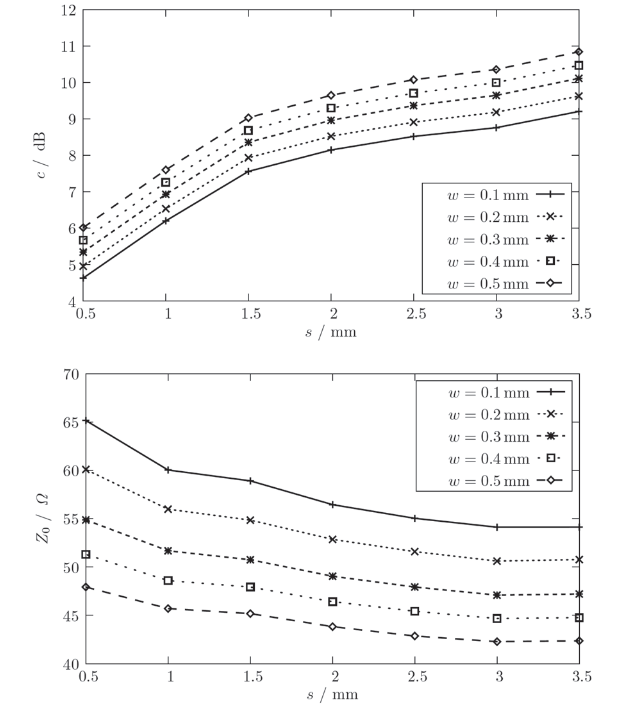

Fig. 4: Typical coupling factors and characteristic impedances with varying *s* and *w* for section type *A* (w_2 is fixed to 0.08 mm).

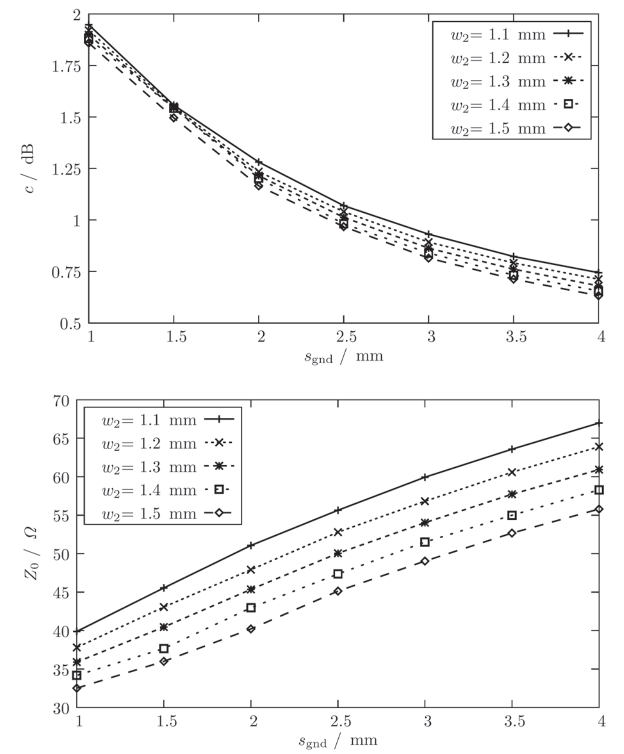

Fig. 5: Typical coupling factors and characteristic impedances with varying parameters for section type *B* ($w_{\text{gnd}} = 2.25$ mm).

For section type *A* the difference between the modal phase velocities is uncritical as the electromagnetic fields are mainly confined within the substrate for both modes and are therefore quite constant (see Fig. 6). But for section type *B* the value of s_{gnd} has to be chosen carefully, as the effective dielectric constant $\varepsilon_{\text{r,eff}}$ of the even mode and, hence, the isolation performance is mainly affected by this parameter.

Frequenz
62 (2008)
9–10

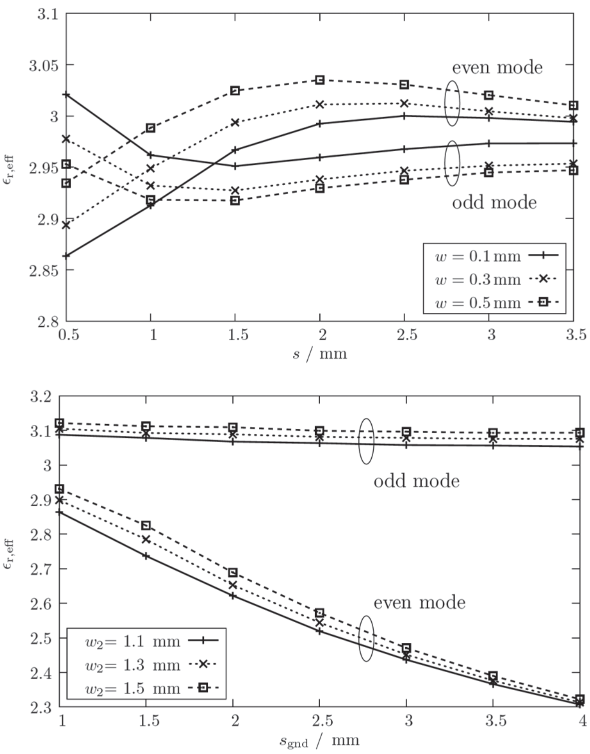

Fig. 6: Effective dielectric constant of the even and odd mode for section type *A* with $w_2 = 0.08$ mm (top) and section type *B* with $w_{gnd} = 2.25$ mm (bottom).

Tab. 1: Design values and dimensions of the coupler.

Design values according to [12]					
c / dB	ripple / dB	section	$Z_{0,even}$ / Ω	$Z_{0,odd}$ / Ω	c_i / dB
		1,5	53.9	46.4	22.4
3.0	±0.1	2,4	68.6	36.4	10.3
		3	198.8	12.6	1.1
	Physical dimensions / mm				
section	w	s	w_2	w_{gnd}	s_{gnd}
1,5	1.11	0.73	-	-	-
2,4	0.3	2.5	0.08	-	-
3	-	-	1.3	2.25	2.5

3.2 Design of an Ultra-Wideband Coupler

The design values for a five-sectional 3 dB coupler with a theoretical relative bandwidth of 132 % and a center frequency of 6.85 GHz are listed in Tab. 1 together with the physical dimensions obtained by the previously described design procedure for the multilayer coupler. The first and last section of the coupler are realized by standard coupled microstrip lines, while section type *A* is used for the second and forth segment acting as a transition to the middle section of type *B*. For section type *A* the distance *s* between the lines is chosen to avoid a discontinuity to the fixed first and last section. The final values are then obtained with the charts partially provided in Fig. 4 and Fig. 5. There, a compromise between a characteristic impedance of 50 Ohm and the ideal coupling value has to be made. In order to obtain an operating frequency range of 3.1 – 10.6 GHz, the length of each section is adjusted to be $\lambda/4$ at the center frequency. The propagation constant of the even and odd mode is determined for each

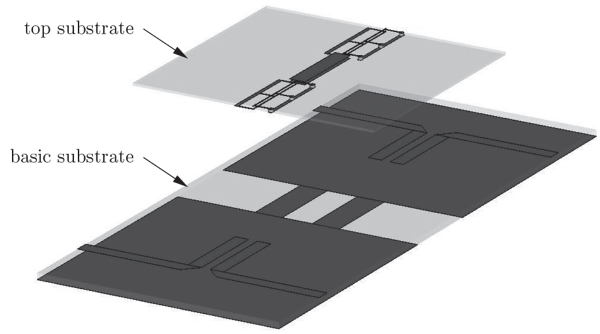

Fig. 7: Detailed view of the two separate substrates of the multilayer coupler.

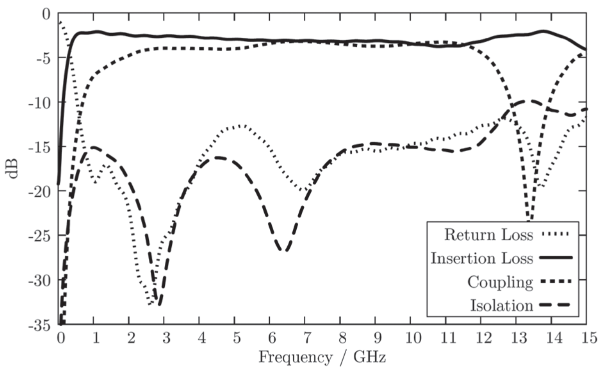

Fig. 8: Simulation results for the designed ultra-wideband coupler.

section, then the mean value is calculated and, therewith, the wavelength is calculated.

In Fig. 7 the structure of the complete five-section coupler is depicted, where the top substrate is lifted and the substrates are drawn trans
parent to get a better view of the different metal parts. The small, high impedance lines and the vias for the connections in section type *A* can be recognized. This circuit is simulated without any additional optimization and the results are shown in Fig. 8. As can be seen, the desired ultra-broadband behavior is obtained.

4. Realization and Measurement Results

The coupler according to the previous chapter has been fabricated and fixed on an aluminum mount (see Fig. 9). The top and basic substrates are joined by epoxy and conductive glue. The proper positioning of the substrates is ensured by alignment pins. At the center of the mount an invisible cavity is located to retain the electrical characteristic of section type *B*. The dimensions of this cavity are optimized for minimum influence on the original structure and space. If only small cavities for integration purposes are applicable, the influence of a fixed cavity could be included in the design procedure. SMA connectors are used for the transition from microstrip lines to coaxial cables. The dimensions of the complete structure are 60 mm x 30 mm.

The measurement results of the realized coupler, shown in Fig. 10, are recorded by an HP8510 network analyzer using a TRL calibration. The return loss and isolation in the intended operating frequency range 3.1 – 10.6 GHz are better than 14 dB. In Fig. 11 a comparison with the simulation results for the transmission and coupling case is depicted, showing that simulation and measurement results agree quite well. For

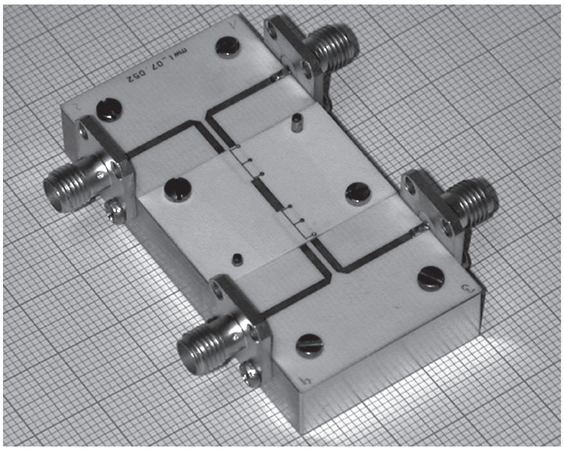

Fig. 9: Picture of the realized multilayer 3 dB directional coupler.

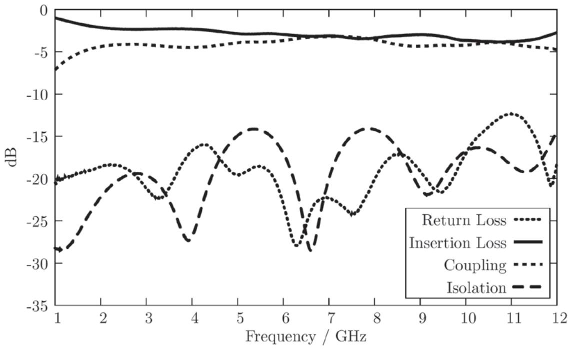

Fig. 10: Measurement results for the ultra-wideband 3 dB directional coupler.

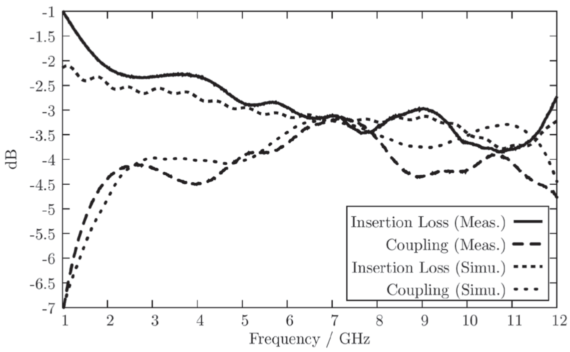

Fig. 11: Comparison between measurement and simulation for the transmission and coupling case.

lower frequencies the gap between coupling and transmission increases, so the coupling and insertion loss in the interesting frequency range is 3.4 dB ± 1.1 dB.

The group delay of the coupler is presented in Fig. 12 for simulation and measurement, where a smoothing is performed for the measured data in order to be able to compare the curves. As can be seen both results agree very well, and the obtained flat characteristics with a variation of ±25 ps indicate that the coupler is suited for impulse radiating systems.

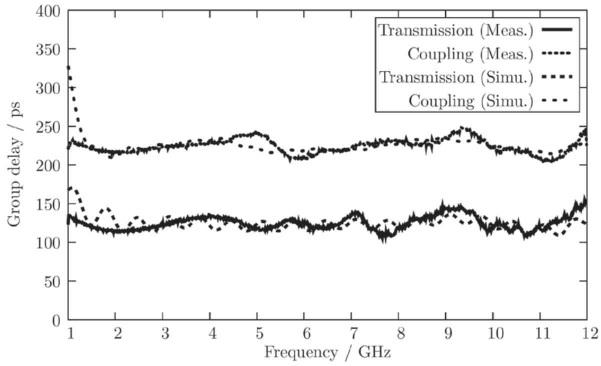

Fig. 12: Simulated and measured group delay for the transmission and coupling.

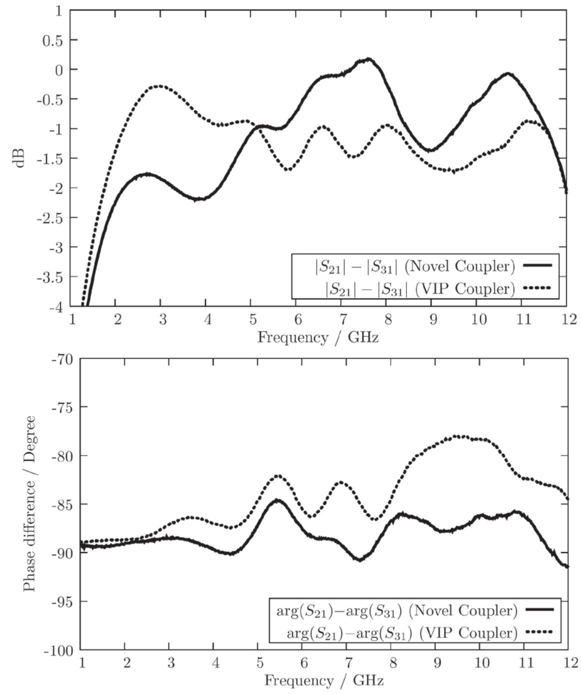

Fig. 13: Amplitude and phase difference between the transmission and coupling port for the measurement results of both coupler types.

5. Comparison Multilayer and VIP Coupler

A similar electrical performance is obtained for the manufactured multilayer and the VIP coupler (compare Fig. 2 and Fig. 10), when both couplers are designed with the same specifications (frequency range, ripple). The maximum values for isolation and return loss are 15 dB ± 1 dB for both couplers and the group delay variations are almost identical. However, there are some differences in the transmission and coupling behavior. In Fig. 13 the amplitude and phase errors of both couplers are shown. The amplitude difference is slightly better for the VIP coupler with ±0.75 dB in comparison to the multilayer coupler with ±1.1 dB. Regarding phase error, the multilayer coupler achieves a better performance with $88 \pm 3^\circ$ compared to $84 \pm 5^\circ$ for the VIP coupler.

6. Conclusion

In this paper a general design procedure has been presented showing how to realize multisectional ultra-wideband directional couplers. This method has been applied to the design of a novel multilayer coupler. There, two structures for medium and tight coupling are derived by the VIP coupler structure leading to a robust overall structure and easily producible coupler with a similar electrical performance like the VIP coupler.

In the design process for the multilayer coupler several parameters like height and permittivity of the top substrate are kept constant. For different coupler specifications these parameters could be changed gaining more flexibility in the design.

7. References

[1] Federal Communications Commission, "Revision of part 15 of the commission's rules regarding ultra-wideband transmission systems", Washington D.C., USA, First Report & Order 48–02, Apr. 2002.

[2] R. J. Fontana, "Recent system applications of short-pulse ultra-wideband (UWB) technology," IEEE Transactions on Microwave Theory and Techniques, vol. 52, no. 9, pp. 2087–2104, Sep. 2004.

[3] Matthaei, George L.; Young, Leo; Jones, E. M. T., Microwave Filters, Impedance-Matching Networks, and Coupling Structures. McGraw-Hill Book Company, 1964.

[4] G. Kemp, J. Hobdell, and J. Biggin, "Ultra-wideband quadrature coupler," Electronics Letters, vol. 19, no. 9, pp. 197–199, Mar. 1983.

[5] J. Walker, "Analysis and design of Kemp-type 3-dB quadrature couplers," IEEE Transactions on Microwave Theory and Techniques, vol. 38, no. 1, pp. 88–90, Jan. 1990.

[6] S. B. Cohn, "The re-entrant cross section and wide-band 3-dB hybrid couplers," IRE Transactions on Microwave Theory and Techniques, vol. 3, pp. 29–38, 1955.

[7] M. M. Fahmi, J. A. Ruiz-Cruz, K. A. Zaki, and A. J. Piloto, "Multilayer multi-section broadband LTCC stripline directional couplers," in IEEE International Symposium on Microwave Theory and Techniques, Jun. 2007, pp. 173–176.

[8] A. M. Abbosh and M. E. Bialkowski, "Design of compact directionalcouplers for UWB application," IEEE Transactions on Microwave Theory and Techniques, vol. 55, no. 2, pp. 189–193, Feb. 2007.

[9] A. M. Abbosh and M. E. Bialkowski, "Design of ultra wideband quadrature microstrip/slot coupler," Microwave and Optical Technology Letters, vol. 49, no. 9, pp. 2101–2103, Sep. 2007.

[10] Y. Konishi, I. Awai, Y. Fukuoka, and M. Nakajima, "A directional coupler of a vertically installed planar circuit structure," IEEE Transactions on Microwave Theory and Techniques, vol. 36, no. 6, pp. 1057–1063, Jun. 1988.

[11] H.-C. Chen and C.-Y. Chang, "Modified vertically installed planar couplers for ultrabroadband multisection quadrature hybrid," IEEE Microwave and Wireless Components Letters, vol. 16, no. 8, pp. 446–448, Aug. 2006.

[12] E. Cristal and L. Young, "Theory and tables of optimum symmetrical TEM-mode coupled-transmission-line directional couplers," IEEE Transactions on Microwave Theory and Techniques, vol. 13, no. 5, pp. 544–558, Sep. 1965.

[13] Advanced Design System 2006, Agilent Technologies Inc, website: http://eesof.tm.agilent.com.

[14] Microwave Studio 2006B, CST-Computer Simulation Technology, website: http://www.cst.com.

This work has been funded by the German Research Foundation (DFG) under the program UKoLoS.
Website: http://www-emt.tu-ilmenau.de/ukolos/

Mario Leib, Dennis Mack, Felix Thurow and Wolfgang Menzel
Microwave Techniques, University of Ulm
Albert-Einstein-Allee 41, 89081 Ulm

Fax: +49 (0)731/50–26359
E-mail: mario.leib@uni-ulm.de