Design of a Multilayer Ultra-Wideband Directional Coupler

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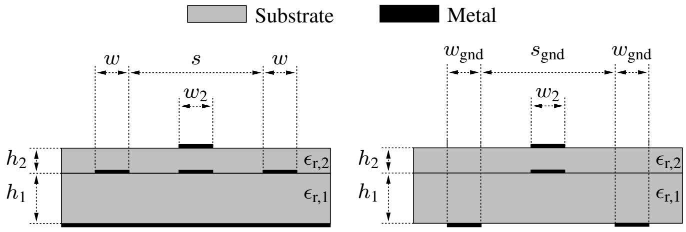
***Abstract*—The design of a planar, ultra-wideband, five-section 3 dB directional coupler is presented. In order to achieve the necessary tight coupling at the center section for the desired ultra-broadband behavior, a novel multilayer configuration is used. This multilayer structure leads to a compact, robust and easily producible realization. The design procedure itself is done without a time-consuming full-wave analysis and can be applied easily to other coupler designs. The manufactured coupler has a coupling and insertion loss of 3.4 dB ± 1.1 dB and an isolation and return loss of better than 14 dB in the operating bandwidth between 3.1-10.6 GHz.**

***Index Terms*—Microstrip directional couplers, ultra-wideband (UWB), planar, multilayer**



(a) Section type *A* (b) Section type *B*

Fig. 1. Cross sections of the novel multilayer coupling sections.

I. 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]. There, directional couplers are of general interest for power division and combination, duplexers and beamforming 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 cheap 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 occupies much more substrate area as two couplers with a reduced coupling are combined. Another way to obtain a tight coupling is a vertically installed planar hybrid [8], where a thin substrate is added perpendicular to the main circuit. In [9] a multisection directional coupler is realized in such a way, where additional dielectric blocks are put at the side of the vertical substrate for stabilization purposes and equalization of the modal phase velocities. Using this method a broadband behavior with a relative bandwidth of 160% has been achieved by a five-section coupler, but the manual attachment of the vertical substrate and the fixing by soldering is a difficult and time-consuming fabrication process. Furthermore, the vertically installed substrate is very sensitive to mechanical forces and therefore quite fragile. The stability can be improved and the mounting of the vertical substrate can be eased by milling a slot in the base substrate. This, however, leads to another fabrication step. In this publication a modified version of this coupler is presented. Instead of a vertical installed substrate a simple multilayer configuration is used leading to a much easier fabrication process, a significant height reduction and a robust structure.

II. Coupler Design

A. General Design Procedure

The basic concept of the broadband coupler are 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 [10] tables with values for $Z_{0,\text{even}}$, $Z_{0,\text{odd}}$ are provided for different bandwidths and ripples in order to design a specific coupler. The characteristic values for coupled microstrip lines can be determined e. g. by [11]. For a wide bandwidth a high coupling is mandatory and leads to line distances, which are impossible to realize in simple microstrip technique. Therefore, in order to design a broadband coupler, two different multilayer section types are proposed in Fig. 1.

Both section types consist of two substrates and three metal layers. Section type *A* has two lines in the center separated by the top substrate and additionally a transmission line at each side. Both inner 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

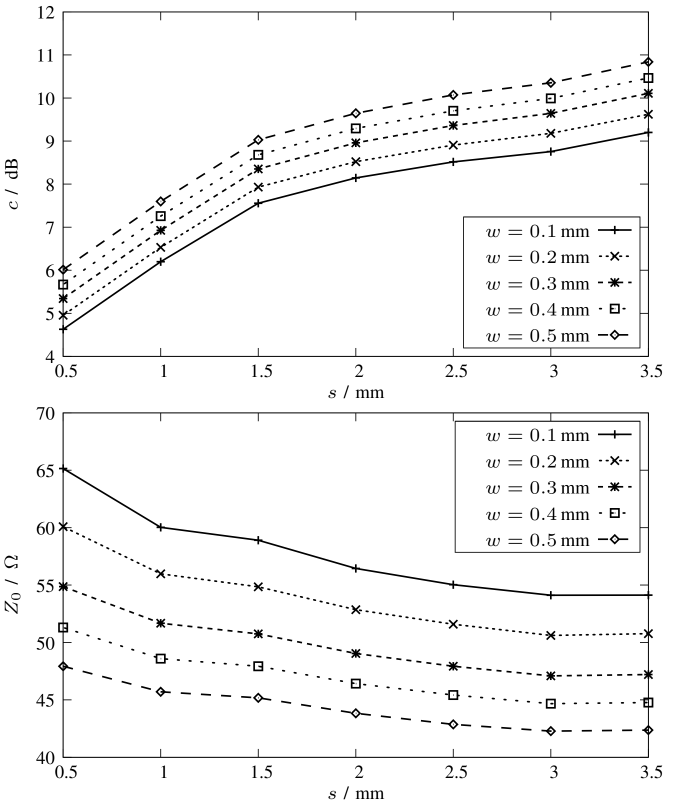


Fig. 2. Typical coupling factors and characteristic impedances with varying s and w for section type *A* (w_2 is fixed to 0.08 mm).

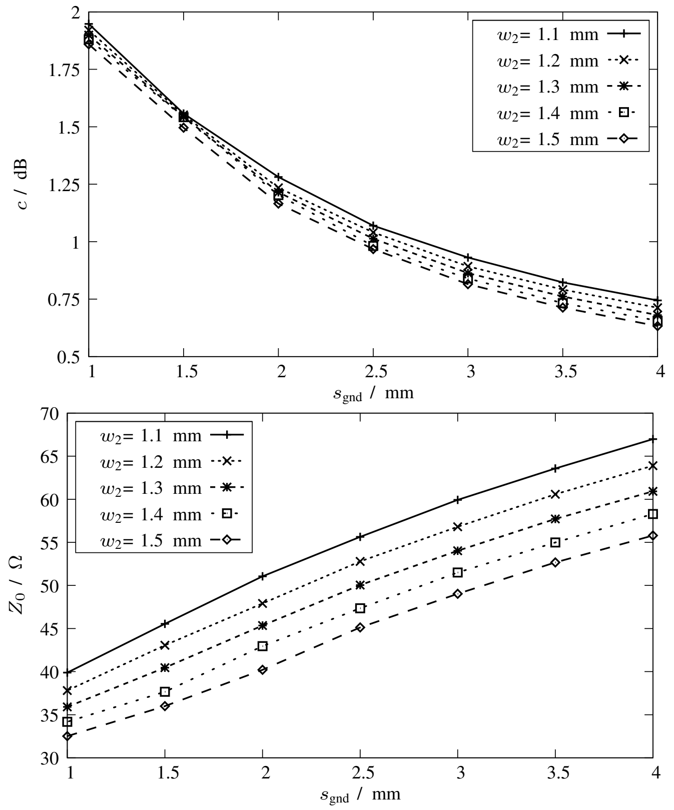


Fig. 3. Typical coupling factors and characteristic impedances with varying parameters for section type *B* (w_{gnd} = 2.25 mm).

get a connection to the top side of the second substrate. So an additional coupling is implemented in the center, resulting in higher coupling values and more degrees of freedom (h_2, $\epsilon_{\mathrm{r},2}$, w_2) compared to coupled microstrip lines. Further, section type *A* can act as a transition between microstrip coupled lines and section type *B*. 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 [12]. Therewith, the characteristic impedance Z_0 and the coupling value c can be obtained for the sections by the following equations:

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

$$c = -20 \lg \frac{(Z_{0,\mathrm{even}}/Z_{0,\mathrm{odd}}) - 1}{(Z_{0,\mathrm{even}}/Z_{0,\mathrm{odd}}) + 1}\,. \tag{2}$$

In Fig. 2 and Fig. 3 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 generated diagrams. For section type *B* s_{gnd} has to be chosen carefully, as the effective dielectric constant $\epsilon_{\mathrm{r,eff}}$ of the even-mode (see Fig. 4) and, hence, the phase velocity is mainly affected by this parameter.

B. Design of an Ultra-Wideband Coupler

The design values for a five-section 3 dB coupler with a theoretical relative bandwidth of 132% are listed in Tab. I together with the physical dimensions obtained by the previously described design procedure. The first and last section are

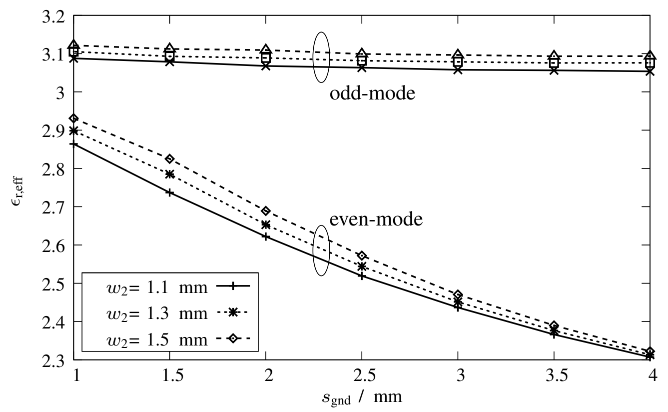


Fig. 4. Effective dielectric constant of the even- and odd-mode for section type *B* (w_{gnd} = 2.25 mm).

TABLE I
DESIGN VALUES AND DIMENSIONS OF THE COUPLER.

Design values according to [10]					
c / dB	ripple / dB	Section	$Z_{0,\text{even}}$	$Z_{0,\text{odd}}$	c_i / dB
3.0	± 0.1	1,5	53.9 Ω	46.4 Ω	22.4
		2,4	68.6 Ω	36.4 Ω	10.3
		3	198.8 Ω	12.6 Ω	1.1

Physical dimensions / mm						
Section	w	s	w_2	w_{gnd}	s_{gnd}	l
1, 5	1.11	0.73	—	—	—	6.7
2, 4	0.3	2.5	0.08	—	—	6.34
3	—	—	1.3	2.25	2.5	6.53

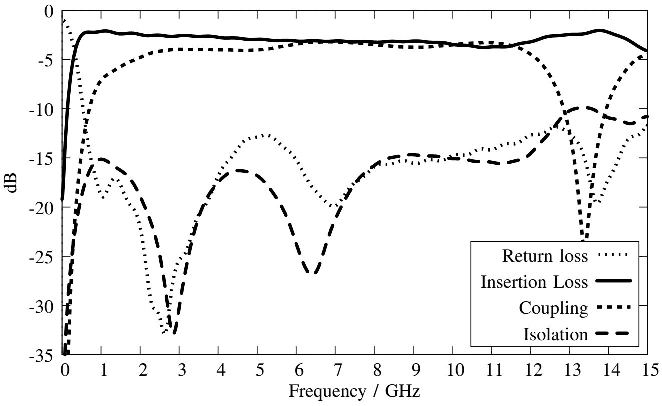


Fig. 6. Simulation results for the designed ultra-wideband 3 dB directional coupler.

realized by 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. 2 and Fig. 3. There, a compromise between a characteristic impedance of 50 Ω and the ideal coupling value has to be made. In order to obtain a operating frequency range of 3.1-10.6 GHz, the length of each section is adjusted to be $\lambda/4$ at the center frequency of 6.85 GHz. Therefore, the propagation constant of the even- and odd-mode is determined for each section, then the mean value is calculated and therewith, the wavelength is calculated.

In Fig. 5 the structure of the complete five-section coupler is depicted, where the top substrate is lifted and the substrates are transparent to get a better view of the different metal parts. There, the small lines and vias for the connections in section type A can be clearly seen. This circuit is simulated without any additional optimization and the results are shown in Fig. 6. As can be seen the desired ultra-broadband behavior is obtained.

III. REALIZATION AND MEASUREMENT RESULTS

The coupler according to the previous chapter has been fabricated and fixed on an aluminum mount (see Fig. 7). 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. SMA connectors are used for transition from microstrip lines to coaxial cables.

The measurement results of the realized coupler, shown in Fig. 8, are recorded by an HP8510 network analyzer with 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. 9 a comparison with the simulation results for the transmission and coupling case is depicted, showing that the simulation and measurement results agree quite well. But, for lower frequencies the gap between coupling and transmission increases, so the coupling and insertion loss in the interesting

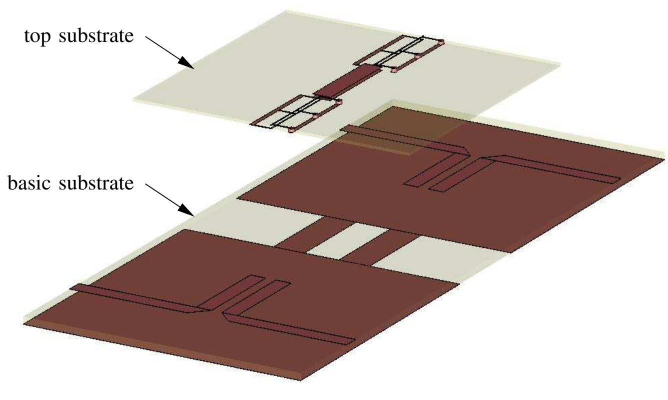


Fig. 5. Detailed view of the two separate substrates of the multilayer coupler.

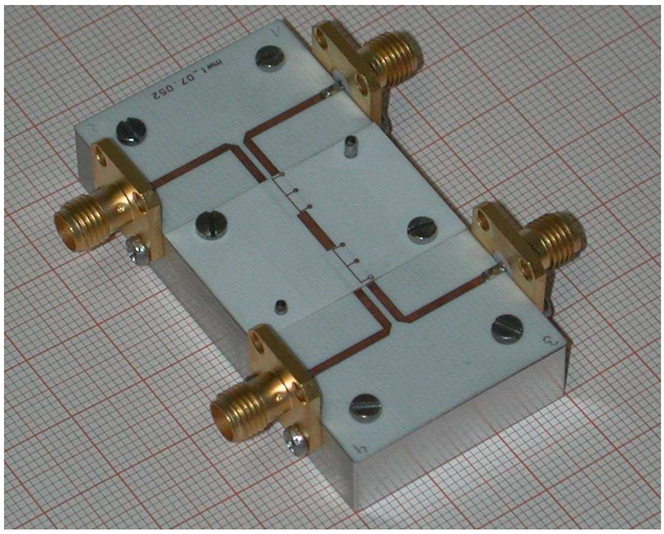


Fig. 7. Picture of the realized 3 dB directional coupler.

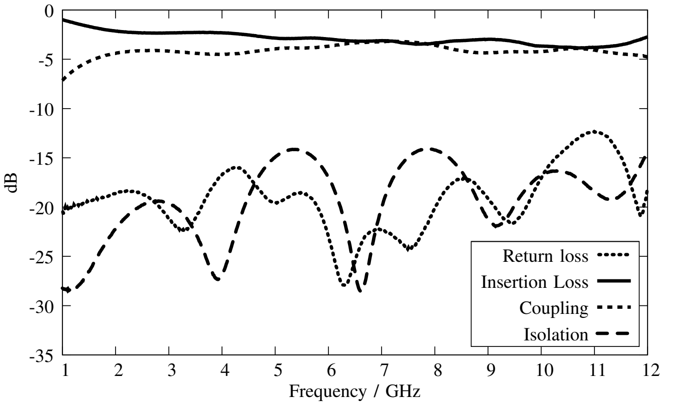


Fig. 8. Measurement results for the ultra-wideband 3 dB directional coupler.

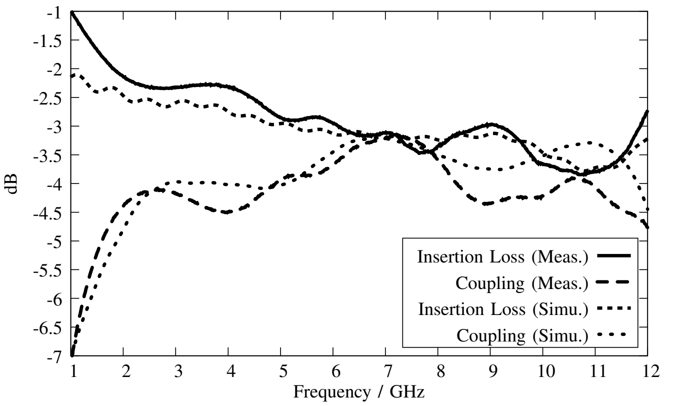


Fig. 9. Comparison between measurement and simulation for the transmission and coupling case.

frequency range is 3.4 dB ± 1.1 dB. For impulse radiating systems the group delay has to be constant over frequency. The group delay of the coupler is presented in Fig. 10. In order to be able to distinguish the different curves, they were manually shifted against each other.

IV. Conclusion

In this paper a design procedure has been presented showing how to realize multisection broadband directional couplers by using multilayer structures for medium and high coupling. No full-wave optimization is needed resulting in a fast design process. Exemplary an ultra-wideband five-section coupler has been fabricated and characterized. In this design process 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.

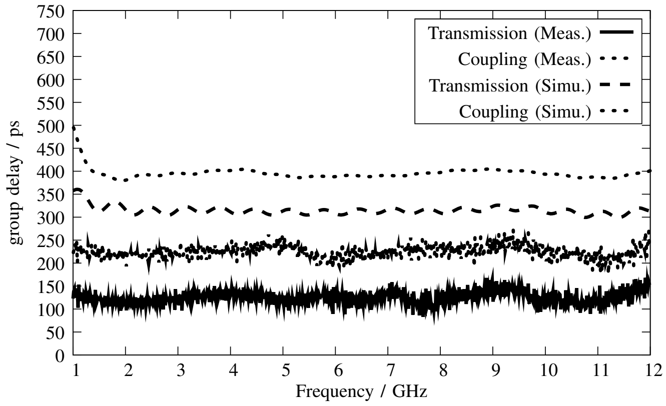


Fig. 10. Simulated and measured group delay for the transmission and coupling case.

V. Acknowledgment

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