Design of quasi-ideal Couplers using Multilayer MMIC Technology

M. Engels and R.H. Jansen

RWTH Aachen, Dept. of El. Engineering, ITHE, Kopernikusstr. 16,
D-52074 Aachen, Germany

Abstract

Mode-related design equations not available to date are presented and discussed for quasi-ideal couplers using multilayer MMIC/MCM technology. The resulting couplers have close-to-zero reflection and near-perfect isolation over very large bandwidths. Several such couplers with varied coupling coefficients have been designed to demonstrate their realizability.

Introduction

To realize quadrature hybrids in integrated circuits, broadside couplers can be used [1], [2], [3]. In the monolithic version, such couplers can be meandered for size reduction [4]. However, in contrast to the planar, symmetric coupler [5], concise mode-related design equations for ideal couplers do not appear to exist, so far. Consequently, these components are usually designed iteratively by optimization of the S-parameters for low reflection, good isolation and 90° phase difference between the direct and the coupled port. Alternatively, the couplers can be designed using the direct method of Tsai and Gupta [6] which results in couplers with low, but finite reflection and isolation, even in the true TEM case.

It has been shown recently by Prouty and Schwarz [7], that broadside couplers in inhomogeneous media (bilevel microstrip) can be designed, which have zero reflection and perfect isolation for all frequencies under quasi-static assumptions. These couplers have again been designed by iterative analysis, and design graphs were given for a special class of such couplers.

In our work, analytical conditions for *perfect* coupler performance based on the relevant mode parameters have been derived and realizability is demonstrated for MMIC technology using 3 metal levels. The conditions were deducted from S-parameter analysis based on the equations given in [8]. To support the complex analytic calculations a commercial mathematics program [9] using symbolic algebra has been applied. The respective geometry required to realize the specified mode parameters can be conveniently determined by automated optimization which — in contrast to using S-parameters as previous authors did — is a well behaved process.

Design equations

The derivation of the design equations starts with the Z-parameters of a section of coupled strips as given in [8]. Analytical conversion of Z-parameters to S-parameters using the well known formula

$$\mathbf{S} = (\mathbf{Z_n} + \mathbf{E})^{-1} \cdot (\mathbf{Z_n} - \mathbf{E}) \quad (1)$$

and setting the reflection and transmission to the isolated port to zero leads to the equations given in [5]. Additionally, the following design equations derived here describe quasi-static coupler performance in terms of mode quantities:

$$R_c R_\pi = 1 \quad (2)$$

$$Z_{c,1} = Z_{ref} \quad (3)$$

$$Z_{\pi,1} = -Z_{ref} \quad (4)$$

$$c = \frac{2R_c}{R_c^2 + 1} \quad (5)$$

Here, R_c and R_π are the voltage ratios of strip 2 to strip 1 of the c- and π-mode, respectively. $Z_{c,1}$ and $Z_{\pi,1}$ are the characteristic impedances of strip 1 of the c- and π-mode, implying a terminology of TEM-mode propagation [8]. Z_{ref} is the coupler's port reference impedance, and c is the coupling coefficient. Note, that a difference in the phase velocities of the modes does not affect the coupler's performance as it does in the case of conventional symmetric couplers. We propose to call such couplers based on (2)–(5) quasi-ideal since they allow for zero reflection and perfect isolation at center frequency even in a non-homogeneous medium as it prevails for multilayer MMICs or microwave multichip modules [10]. Indeed, as will be shown below, they are suitable for close-to-ideal broadband reflection and isolation.

Substituting (2)–(5) into the complex equations for the S-parameters of a finite length section of two coupled strips, the respective general terms reduce to much simpler form, which are similar to the S-parameters of a conventional symmetric TEM-coupler. Assuming the port numbering of Fig. 1, the scattering parameters of a quasi-ideal coupler are given by eq. (6)–(8).

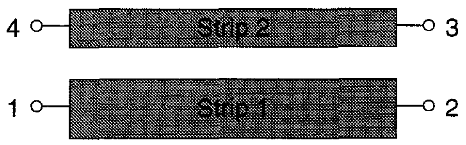

Figure 1: Port numbering used here

$$s_{12} = s_{12,\mathrm{TEM}} \cdot e^{-j\frac{\beta_c-\beta_\pi}{2}\cdot l} \quad (6)$$

$$s_{14} = s_{14,\mathrm{TEM}} \quad (7)$$

$$s_{34} = s_{34,\mathrm{TEM}} \cdot e^{+j\frac{\beta_c-\beta_\pi}{2}\cdot l}. \quad (8)$$

Here, $s_{\nu\mu,\mathrm{TEM}}$ are the respective scattering parameters of a symmetric TEM coupler as given in [5], having a propagation constant of $\beta = (\beta_c + \beta_\pi)/2$. From these specialized equations it can be seen, that the difference of the phase angles of the direct and the coupled port $\Delta\varphi$ is *not* fixed to 90° as prevailing for a symmetric ideal TEM-coupler [5]. Instead, there is a frequency dependent linear deviation from ideal quadrature which, however, can be corrected easily by connecting a transmission line with a length of

$$l_{strip} = \frac{|\beta_c - \beta_\pi|}{2\beta_{strip}} \cdot l_{coupler} \quad (9)$$

to both ports of strip 2, if $\beta_c > \beta_\pi$, or to both ports of strip 1, if $\beta_\pi > \beta_c$.

Design examples

In Fig. 2, a generic 3-layer cross section is shown, which has been used to design several couplers with different substrates and dielectric separation layers. We have found, that these structures are well suited to realize the above design equations for different coupling coefficients, while this seems not to be possible with only 2 metal levels and fixed dielectric constants. In the technology of Fig. 2, the ground plane is placed on top of the substrate, so that no backside processing is necessary. Further, the ground plane spacing s_{gnd} provides an additional degree of freedom, which is needed for easy realization of the postulated mode parameter relations (2)–(5). An additional advantage of this is the small cross-section and the reduction of lateral stray field, so that very compact meander shaped couplers can be designed. Due to the lateral groundplane, the substrate thickness has negligible effect on the mode parameters, so that normalization of the geometry to the

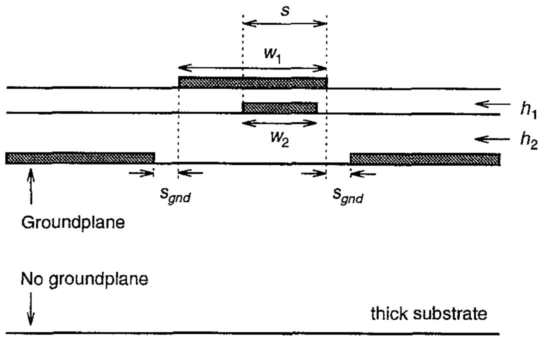

Figure 2: Generic cross-section of a quasi-ideal coupler

thickness of one of the dielectric separation layers is reasonable. Table 1 shows the normalized geometry of quasi-ideal 3 dB couplers on GaAs, Silicon, and Alumina substrate with separation layers consisting of Polyimide ($\varepsilon_r = 3.0$) or Silicon oxynitride ($\varepsilon_r = 5.0$). Designing these

	Polyimide	SiON
GaAs	$h_1 = 0.5$ $w_1 = 2.81$ $w_2 = 1.76$ $s = 1.85$ $s_{gnd} = 0.47$	$h_1 = 1$ $w_1 = 3.86$ $w_2 = 2.38$ $s = 3.26$ $s_{gnd} = 2.95$
Silicon	$h_1 = 0.5$ $w_1 = 2.83$ $w_2 = 1.79$ $s = 1.84$ $s_{gnd} = 0.52$	$h_1 = 1$ $w_1 = 4.19$ $w_2 = 2.54$ $s = 2.47$ $s_{gnd} = 3.49$
Alumina	$h_1 = 0.5$ $w_1 = 2.97$ $w_2 = 1.87$ $s = 1.80$ $s_{gnd} = 0.65$	$h_1 = 1$ $w_1 = 5.57$ $w_2 = 3.46$ $s = 2.01$ $s_{gnd} = 5.28$

Table 1: Geometry of quasi-ideal couplers using different dielectrics (all values normalized to h_2)

couplers by optimization of the mode parameters (not of the S-parameters), we have found, that there are constraints regarding the thickness ratio of the two dielectric layers. Using polyimide, a 3 dB coupling cannot be achieved easily using dielectrics of the same thickness. So, the upper layer has been chosen to have half the thickness. Using Silicon oxynitride however, a tight coupling can be achieved using layers of equal thickness. Note, that the data in Table 1 result from a quasi-static analysis assuming strips of zero thickness. So, using relatively thick conductors or very high frequencies, performance may potentially be deteriorated.

As a design example, Table 2 shows the calculated mode

$R_c = 0.4156$	$\varepsilon_c = 2.497$	$Z_{c,1} = 49.994\,\Omega$
$R_\pi = 2.4152$	$\varepsilon_\pi = 3.351$	$Z_{\pi,1} - 49.741\,\Omega$

$$\Rightarrow \quad R_c \cdot R_\pi = 1.00375$$
$$\Rightarrow \quad c = 0.7088$$

Table 2: Mode parameters of a 3 dB quasi-ideal coupler on GaAs substrate using polyimide separation layers

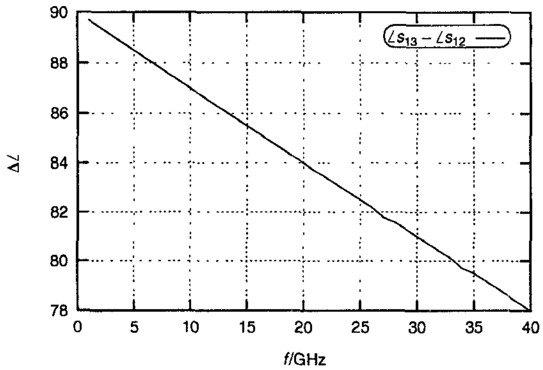

Figure 4: Calculated difference in the phase angles of the direct and coupled port (simulation based on TEM assumption)

parameters of a 3 dB coupler on GaAs substrate using polyimide separation layers. It can be seen, that the equations (2)–(5) have been satisfied there with only a very small residual error using quasi-static EM simulation as in [11].

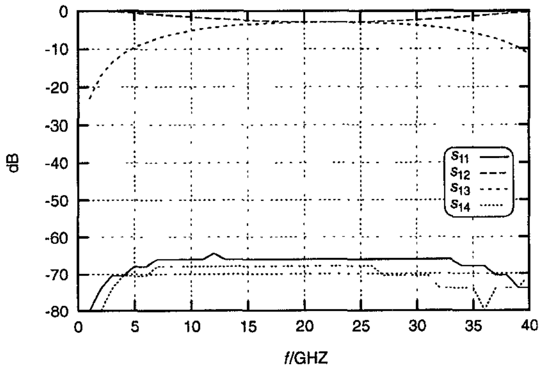

Figure 3: Calculated magnitude of the S-parameters of a quasi-ideal 3 dB coupler (simulation based on TEM assumption)

In fig. 3, the calculated S-parameters — based on the mode parameters of Table 2 — of the quasi-ideal coupler are shown for the straight coupler's length of 2 mm. In the quasi-static analysis (still ignoring frequency dispersion and loss), there is an extremely low reflection and also very low transmission to the isolated port (< -60 dB) for all frequencies. The finite residual values are due to small differences of the mode parameters in Table 2 as compared to (2)–(5). Further, it can be seen in fig. 4, that there is the mentioned frequency dependent linear deviation from ideal quadrature, which can be easily removed [7] adding l_{strip} of eq. (9).

Nevertheless, it is obvious, that in physical reality several effects may result in a deterioration of the ideal performance. Due to the inhomogeneous medium used, the assumption of true TEM-mode propagation is satisfied only approximately, so that the mode parameters become slightly frequency dependent; further the interconnection to feedlines will produce additional reflections. However, due to the small lateral dimensions of the coupler these effects should not be very pronounced. Additional deterioration may be caused by lossy material, and by the fact, that every method used to calculate the mode-parameters has finite accuracy.

Design Verification

To obtain a more realistic view of the coupler's performance, a full-wave 2.5D-EM analysis run of a meandered version of the coupler has been conducted using an inhouse SDA program [12]. Due to limitations regarding the choice of geometry in a regular grid for the analysis program, a coupler with slightly modified cross-section (see Table 3) could be analyzed only.

	h_1	w_1	w_2	s	s_{gnd}
original	3	16.86	10.56	11.1	2.82
modified	3	16	12	12	4

Table 3: Original geometry and geometry of coupler cross-section modified for 2.5D EM simulation [12] (dimensions in micrometers, $h_2 = 6\,\mu$m)

A floor-plan of the meandered structure is shown in fig. 5. The results of the ideal 2D-TEM (straight version) and the rigorous 2.5D analysis (meandered version) are shown in fig. 6 and fig. 7 in comparison. The 2D analysis shows a residual reflection of less than -28 dB and a residual transmission to the isolated port of less than -37 dB, which is caused only by the grid-related modification of the cross-section. The 2.5D analysis results in very small residual values of less than -24 dB and -26 dB, respectively, too. The deviation from ideal quadrature is 0.32°/GHz and 0.4°/GHz in the 2D and the 2.5D analysis, respectively.

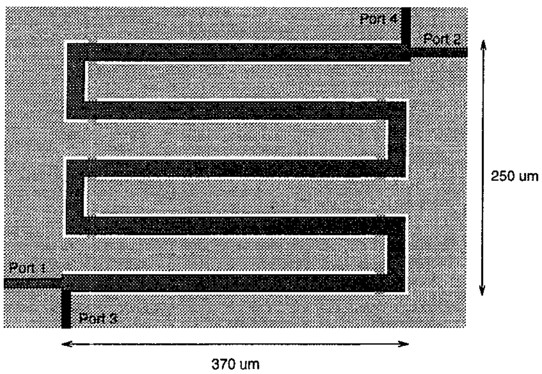

Figure 5: Floor-plan of the meandered broadside-coupler

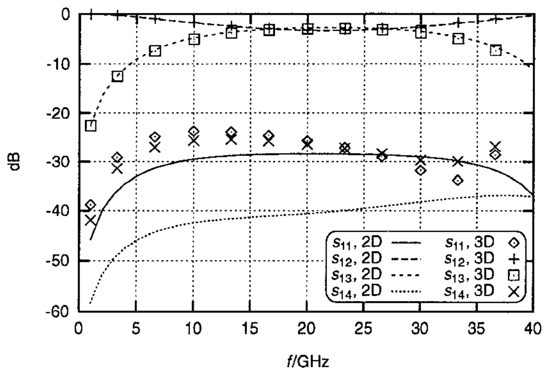

Figure 6: Calculated magnitude of the S-parameters of the meandered coupler (static 2D straight approximation and rigorous 2.5D analysis)

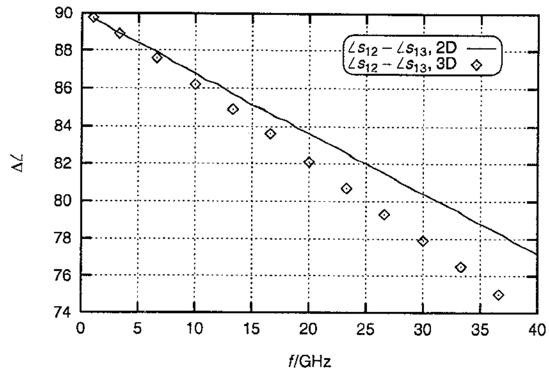

Figure 7: Calculated difference in the phase angles of the meandered coupler (static 2D straight approximation and rigorous 2.5D analysis)

Conclusion

We have presented explicit mode-parameter design equations for broadside-couplers and demonstrated realizability in a multilayer MMIC medium. The resulting structures have the advantage of theoretically ideal performance and very small lateral dimensions, making them suitable for compaction by meandering. Full-wave rigorous 2.5D-EM simulation including parasitic effects confirms that broadband near-ideal performance can indeed be obtained.

References

[1] H.R. Malone. "Microstrip overlay coupler suits broadband use". *Microwave & RF*, vol. 24, no. 7, pp. 84–86, May 1985.

[2] D. Willems and I. Bahl. "An MMIC-compatible tightly coupled line structure using embedded microstrip". *IEEE Trans. Microwave Theory Tech.*, vol. 41, no. 12, pp. 2303–2310, December 1993.

[3] F. Mernyei, I. Aoki, and H. Matsuura. "A novel MMIC coupler, measured and simulated data". In *IEEE MTT-S Int. Microwave Symp. Digest*, pp. 229–232, May 1994.

[4] I. Toyoda, T. Hirota, and T. Tokumitsu. "Multilayer MMIC branch-line coupler and broad-side coupler". In *IEEE Microwave and Millimeter-Wave Monolithic Circuits Symposium*, June 1992.

[5] B.M. Oliver. "Directional electromagnetic couplers". *Proc. IRE*, vol. 42, no. 11, pp. 1686–1692, Nov. 1954.

[6] C.M. Tsai and K.C. Gupta. "A Generalized model for coupled lines and its applications to two-layer planar circuits". *IEEE Trans. Microwave Theory Tech.*, vol. 40, no. 12, pp. 2190–2198, December 1992.

[7] M.D. Prouty and S.E. Schwarz. "Hybrid couplers in bilevel microstrip". *IEEE Transactions on Microwave Theory and Techniques*, vol. 41, no. 11, pp. 1939–1944, Nov. 1993.

[8] V.K. Tripathi. "Asymmetric coupled transmission lines in an inhomogeneous medium". *IEEE Trans. Microwave Theory Tech.*, vol. MTT-23, no. 9, pp. 734–739, September 1975.

[9] S. Wolfram. "Mathematika ver. 2.2". Software and users manual. Wolfram Research, Champain, Illinois, USA.

[10] R.G. Arnold and D.J. Pedder. "Microwave characterization of microstrip lines and spiral inductors in MCM-D technology". *IEEE Trans. on Components, Hybrids, and Manufacturing Technology*, vol. CHMT-15, no. 6, pp. 1038–1045, December 1992.

[11] M. Engels and R.H. Jansen. "A hybrid technique for modeling stacked MMIC components including 3D capacitance and conducter thickness effects". In *1994 Asia-Pacific Microwave Conference Proc.*, pp. 515–518, 1994.

[12] A. John and R.H. Jansen. "From network theory towards field theory for (M)MIC chip level simulation". In *Proc. 24th European Microwave Conference*, pp. 1072–1077, France, 1994.