Generic Design Methodology for Symmetrically Coupled Line Structures

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Abstract: *High performance miniaturised and cost effective passive components are needed to enable commercially viable novel system level architectures for third generation wireless communication systems. In recent years there has been increasing interest in utilising passive multi-layer IC technologies to integrate Digital and RF functionality in a 3D manner. Examples of such enabling technologies that can potentially deliver such passive components are, multi-layer organic, multi-layer ceramic and/or multi-layer thin film deposition technology [1][2][3].*

Coupled line structures are basic building blocks of such functions as digital-interconnect, RF hybrids, and filters. The main hindrance in the use of such components has been the difficulty in translating the physical layout of multi-layer embedded, coupled line structures into a usable circuit design equivalent model. In this paper, a generic and numerically efficient method of estimating the basic circuit model parameters of arbitrary embedded symmetrically coupled lines is presented.

1. Introduction.

System level architectures for third generation wireless systems require greater integration between RF and base-band functionality. As a result, renewed demand has been generated for high performance, cost-effective, and miniaturised passive components. Multi-layer technologies have gained greater attention in recent years, because of their potential in addressing these needs. Examples of such promising technologies include multi-layer organic, multi-layer ceramic, and/or thin film deposition [1][2][3].

The coupled line structure is a basic building block of such functions as digital-interconnect, RF hybrids and filters. The main hindrance in the design of such structures, on a multi-layer integrated technology, has been the difficulty in translating the physical layout of a multi-layer coupled line structure into a usable circuit design equivalent model. This paper presents a generic and numerically efficient technique of estimating the circuit design model parameters of symmetrically coupled line structures. The method utilises commercial EM simulation packages, in order to model accurately the coupling characteristics of coupled structures. The design of a buried Lange coupler is then considered to demonstrate the application of the proposed technique. Simulation results are presented.

2. Derivation of Methodology.

The circuit model for symmetrically coupled lines can be defined in terms of two normal modes, [4]. The parameters needed in the design of coupled line structures are the even and odd mode characteristic impedance (Z_{oe} and Z_{oo}) and their respective effective dielectric constants (ε_{effe} and ε_{effo}). Analysing individual modes of propagation along two coupled lines by network analysis techniques yields expressions for the design parameters. The expressions assume quasi-TEM propagation, and symmetry of structure. Both these assumptions hold in the case of a pair of embedded symmetrically coupled transmission lines at low microwave frequencies. The ports of the 4-port network, used in the analysis, is defined with port 1 as the input port, and ports 2, 3 and 4 being the direct, isolated, and coupled ports respectively.

Starting with the ABCD-matrix for even and odd mode excitation [5], we can express the design model parameters in terms of S-parameters, as follows:

$$a = \frac{-j(S_{11}+S_{41})}{(S_{21}+S_{31})\sin\beta_e l} \pm \sqrt{1-\frac{(S_{11}+S_{41})^2}{(S_{21}+S_{31})^2\sin^2\beta_e l}} \qquad (1) \qquad \text{Where } a = Z_{oe}/Z_o$$

$$b = \frac{-j(S_{11}-S_{41})}{(S_{21}-S_{31})\sin\beta_o l} \pm \sqrt{1-\frac{(S_{11}-S_{41})^2}{(S_{21}-S_{31})^2\sin^2\beta_o l}} \qquad (2) \qquad \text{Where } b = Z_{oo}/Z_o$$

$$\beta_e = \frac{2}{l}\tan^{-1}\left(\mathrm{Re}\left[\frac{1}{2a\left[1+\left(S_{21}+S_{31}\right)\right]}\left\{j\left(S_{21}+S_{31}\right)\left(a^2+1\right)\pm\sqrt{\left(j\left(S_{21}+S_{31}\right)\left(a^2+1\right)\right)^2-2a\left(1+\left(S_{21}+S_{31}\right)\right)\left(1-\left(S_{21}+S_{31}\right)\right)}\right\}\right]\right) \qquad (3)$$

$$\beta_o = \frac{2}{l}\tan^{-1}\left(\mathrm{Re}\left[\frac{1}{2b\left[1+\left(S_{21}-S_{31}\right)\right]}\left\{j\left(S_{21}-S_{31}\right)\left(b^2+1\right)\pm\sqrt{\left(j\left(S_{21}-S_{31}\right)\left(b^2+1\right)\right)^2-2b\left(1+\left(S_{21}-S_{31}\right)\right)\left(1-\left(S_{21}-S_{31}\right)\right)}\right\}\right]\right) \qquad (4)$$

Note that $\varepsilon_{effn} = \left(\frac{c\beta_n}{2\pi f_0}\right)^2$ where $n = e, o$ and f_0 is the central frequency of the structure.

Expressions (1)-(4) cannot be solved analytically. However, by applying an iterative numerical method a convergent solution can be attained. For this we would require a good initial value. We can derive the following expressions, which give good approximate unique solutions for normalised Z_{oe} and Z_{oo}, with the assumption that $\theta_e = \theta_o = \pi/2$:

$$a = \frac{1 \pm \sqrt{1-4\left(S_{21}+S_{31}/-2j\right)^2}}{2\left(S_{21}+S_{31}/-2j\right)} \quad (5) \qquad\qquad b = \frac{1 \pm \sqrt{1-4\left(S_{21}-S_{31}/-2j\right)^2}}{2\left(S_{21}-S_{31}/-2j\right)} \quad (6)$$

Convergence relies on the appropriate choice of root in expressions (1)-(6). Expressions (5) and (6), depend on whether a and b, are smaller or greater than one. It is advisable that the normalising port impedance is chosen smaller than the anticipated value of Z_{oe} and Z_{oo}. In that case the positive roots would yield the correct result (the opposite is true for a and b smaller than one). For expression (3) and (4) both roots are correct, but only one yields the more accurate result. Utilising the assumption made in the derivation of (5) and (6), (were we assumed that, $\theta_e = \theta_o = \theta = \beta l = \pi/2$), whichever root of (3) and (4) yields the result, $\beta l = \pi/2$ when substituted with the values of a and b from (5) and (6) is the correct root. In the case of (1) and (2), only the positive root is physically valid.

3. Outline of Design Methodology

The proposed procedure for the design of arbitrary coupled line structures on multi-layer substrate can be summarised in the following 6 steps:

1. Choose desired structure of a pair of symmetrical coupled lines (e.g. microstrip, stripline etc.)
2. Calculate the 4-port S-parameters of the structure using an EM simulator at the frequency where the coupler is $\lambda/4$ long.
3. Use equations (5) and (6) to calculate the initial values of Z_{oe} and Z_{oo} assuming $\theta_e = \theta_o$.
4. Substitute the initial values of Z_{oe} and Z_{oo}, calculated in the previous step, into expressions (3) and (4). Then substitute the resulting values into (1) and (2). The new values of Z_{oe} and Z_{oo}, calculated from (1) and (2) should then be substituted once again into (3) and (4).
5. Carry on iterating in this manner until values of Z_{oe}, Z_{oo}, ε_{effe} and ε_{effo} converge.
6. Alter the geometrical parameters of the coupled lines Using Table 1 as a guide, until the desired Z_{oe} and Z_{oo} for specific coupling is obtained.

The desired Z_{oe} and Z_{oo} for specific coupling can be obtained from ref. [6]. Designing coupled structures at a lower frequency, to avoid parasitic effects can attain improved design accuracy. The design can be scaled back to the desired frequency once the design is completed.

Table 1: Behavioural variation guideline for strip based coupled line geometrical parameters, and Z_{oe} and Z_{oo}.

Geometry parameter	Zoe	Zoo
↑W	↓ Zoe	↓ Zoo
↓ W	↑ Zoe	↑ Zoo
↑ S	↓ Zoe	↑ Zoo
↓ S	↑ Zoe	↓Zoo
↑ H	↑ Zoe	↓ Zoo
↓ H	↓ Zoe	↑ Zoo
Key:- Increase (↑); Decrease (↓); Width (W); Separation (S); Substrate Height (H).		

4. Design Example.

The Lange coupler is the best known and widely used 90°-hybrid structure. Julius Lange originally proposed the Lange coupler configuration in 1969 [7]. It typically finds application in balanced designs, such as, balanced amplifiers, mixers, and modulators. We apply the proposed technique and use it in the design of an embedded 4-element Lange coupler. Using ref. [6], 3-dB coupling from a 4-element coupled line structure, is obtained for Z_{oe}=176.41Ω and Z_{oo}=52.54Ω, respectively.

We assume a multi-layer substrate of thickness 1.26mm and dielectric constant of $\varepsilon_r = 7.8$. A pair of microstrip coupled lines were simulated first on the surface and then embedded 100 um down in the same substrate. In this way the design methodology was performed for a reference surface case (for which design equations exist e.g. [8]), and a 2nd case of an embedded micorstrip coupled line scenario where the design cannot be easily pursued by other means. For the surface case bond-wires in air were assumed while for the buried case vias and connecting strips underneath the coupled lines were used. The geometry of the surface and buried Lange couplers are shown in Figure 1.

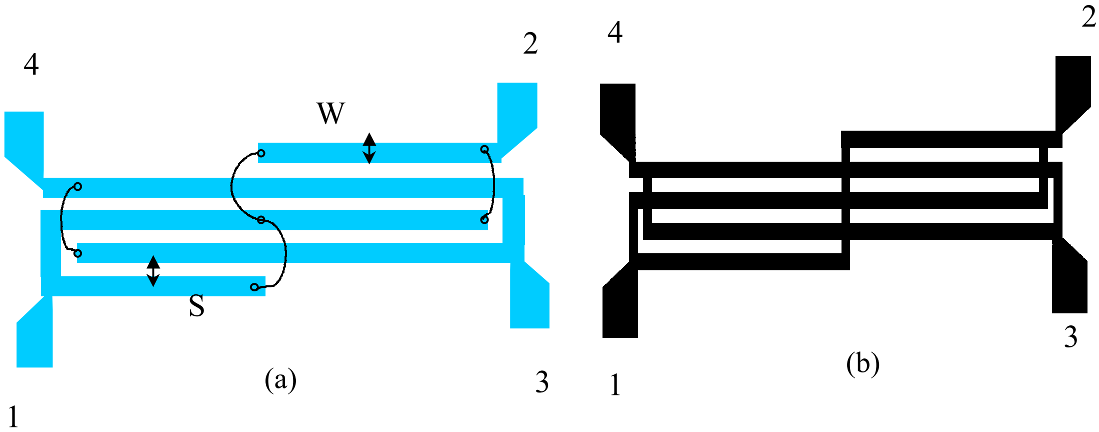

Figure 1: (a) Surface Lange Coupler using wire bonds in air
(b) Embedded Lange Coupler employing vias and buried strips

ADS Momentum was utilised as the EM simulator for performing the numerical iterations and the design procedure outlined in section 3. After evaluating the Z_{oe} and Z_{oo} from expressions (1)-(6), the dimensions of the coupled lines were altered in order to achieve the desired Z_{oe} and Z_{oo} values. Due to the almost proportional nature between changes in geometry and changes in Z_{oe} and Z_{oo} it was possible to produce a design with only three iterations of the procedure. For the surface case it was found that a line width of 150µm, and separation of 100µm, corresponded to Z_{oe} and Z_{oo} values of, 179.17Ω and 51.69Ω, and ε_{effe} and ε_{effo} of 4.633 and 4.554 respectively. For the embedded case for a line width of 150µm and a separation of 125µm, the Z_{oe} and Z_{oo} values were calculated as 159.60Ω and 44.48Ω and ε_{effe} and ε_{effo} were 5.244 and 6.815 respectively. The embedded case was purposely designed to have the coupled lines slightly over-coupled so as to improve amplitude balance bandwidth. The lengths of the coupled line sections were arranged to be $\lambda/4$ at a centre frequency of 1.9GHz. The phase balance for the surface case was found to be 1.5 ^{o}. At least 15 dB of matching and isolation were achieved for both the surface and embedded cases. The amplitude balance bandwidth and phase balance for the embedded case was approximately 55% and 0.5^{o} respectively for the same conditions as the reference surface case. The embedded coupler was 10% smaller in length when compared to the surface case.

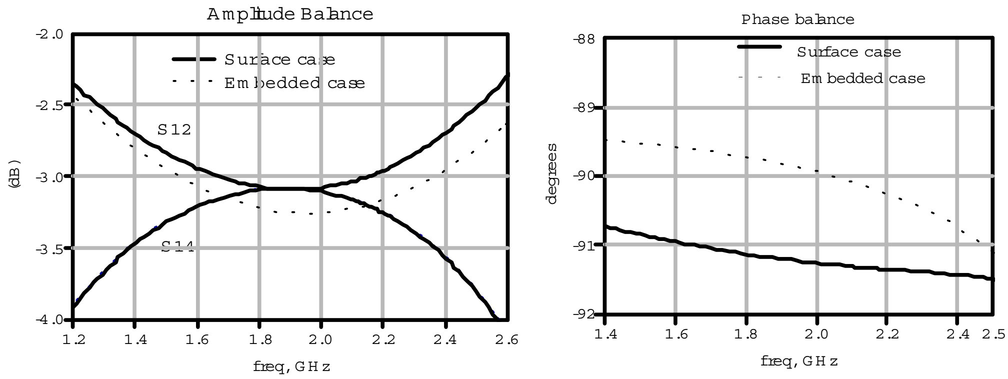

Figure 2: Amplitude and Phase Balance of Surface and Embedded Lange Coupler Designs

5. Conclusion

We have presented a generic circuit model extraction method for arbitrary cross section symmetrical coupled lines embedded in a multi-layer substrate. The proposed design procedure enables the efficient design of high quality and performance passive coupled structures in multi-layer technologies. A Lange Coupler embedded in a multi-layer substrate was designed to demonstrate the utility of the technique.

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