Design of High Directivity Directional Couplers in Multilayer Ceramic Technologies

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Abstract — **Greater amalgamation of transceiver functionality, is a way of addressing the commercial viability of forthcoming architectures. Multilayer Cofired Ceramics (e.g. LTCC/HTCC) is seen, as a potential integration platform offering size, cost and performance advantages. Monolithic integration of passive components, such as directional couplers, in Multilayer Integrated Circuit technologies is highly desirable. Microstrip broadside-coupled structures are well suited for tight coupling in a multilayer high integration environment. However, it is well known that such hybrids suffer from poor directivity due to the inhomogeneous nature of the substrate. Numerous compensation techniques have been proposed in the literature, which attempt to equalize the normal mode phase velocities. In this paper we address the equalization of couplers where the even mode phase velocity is greater than the odd mode, a case typically encountered in broadside-coupled microstrip structures. Simulation and measurement results of practical structures on LTCC technology show that the technique is well suited for multilayer design.**

I. INTRODUCTION

Multilayer Integrated Circuit technologies are seen as the hardware platforms of the future. Such platforms have the potential to meet the size, cost and performance requirements of architectures proposed for 3G/4G. Multilayer Ceramic Integrated Circuit (MCIC) technologies such as Low Temperature Cofired Ceramics (LTCC) are growing in popularity as candidates for such an integration platform. The potential of combining baseband and RF circuit functionalities will enable mixed signal systems to be realized cost effectively. The scenario envisaged in the medium term is one of combining Digital ASICs and RFICs with high density interconnect and miniaturized passive components in what is referred to as a Multi-Chip Module (MCM), Figure 1 illustrates this scenario.

Integrating monolithically passive components such as directional couplers is highly desirable. Microstrip is the most flexible structure for realizing directional couplers in multilayer topologies, however it is well known that such hybrids suffer from poor directivity. The inhomogeneous nature of the substrate means that the normal mode phase velocities are unequal. Numerous techniques have been published based on the principle of equating the phase velocities in order to improve directivity. D. Paolino [1] suggested the used of dielectric overlay to improve isolation, while S. L. March [2] considered the use of pseudo-suspended substrate stripline. A. Podell [3] proposed a technique where the adjacent conductors serrate the space between them, and M. Dydyk's [4] analysis produced closed form expressions for lumped elements between edge coupled structures providing compensation.

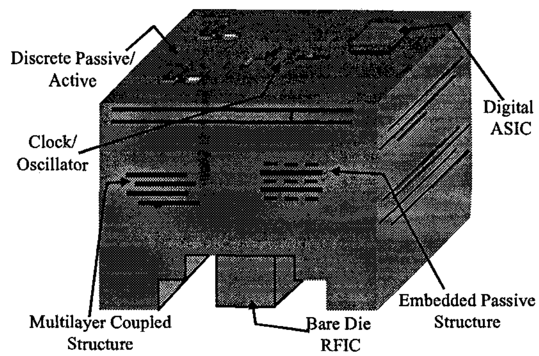

Figure 1. Illustration of MCM scenario

Broadside coupled structures are well suited for tight coupling in multilayer technologies. The broadside coupler can be meandered [5] or spiraled [6] to produce miniaturized, low cost structures without suffering from excessive manufacturing tolerance for high coupling coefficients [7]. Compensating for the difference in normal mode phase velocities in a broadside-coupled structure has not been dealt with by other publications. This paper will present a novel technique for the compensation of broadside couplers by the use of capacitance to ground [10]. Simulation results of broadside microstrip couplers in LTCC substrate will show that it is possible to obtain almost ideal isolation at all four ports at the frequency were the coupler is $\lambda/4$. Simulation results will also show that noticeable improvement in the directivity over the amplitude balance bandwidth can also be achieved. These simulated results are accompanied with measurement results, which show this technique to be viable for practical structures in multilayer LTCC package technologies.

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II. BRIEF OUTLINE OF PRINCIPLE

A. *Introduction to the Principle*

It is well established that symmetrically coupled structures can be modeled as the superposition of two normal modes known as the even and odd mode [8]. The paper by Dydyk [4] demonstrated how capacitive compensation between the plates effected the odd mode, allowing us to equate the odd mode phase velocity with the even mode by the appropriate choice of capacitance. This arraignment is only effective with edge-coupled type topologies, since the odd mode phase velocity is "faster" than the even mode. However for microstrip broadside-coupled structures, it is the even mode phase velocity, which is faster than the odd mode. Placing capacitors to ground (see Figure 2), instead of between the plates, would have the effect of "slowing down" the even mode propagation. Appropriate choice of capacitance will allow us to equate the phase velocities at the central frequency.

B. *First Order Estimate of capacitor values*

The conventional means of representing the normal modes of propagation is by the concept of mutual and self-capacitance. A first approximation for the capacitance value can be derived from this concept.

From reference [9] the even mode capacitance is given by:

$$C_e = \sqrt{\varepsilon_{effe}} \Big/ cZ_{oe} \tag{1}$$

Where ε_{effe} is the effective dielectric constant associated with the even mode and "c" is the speed of light in free space and Z_{oe} is the even mode impedance. If we now equate ε_{effe} with ε_{effo}, where ε_{effo} is the odd mode effective dielectric constant, and subtract expression (1) from it we obtain:

$$C_{comp} = \left[\left(\sqrt{\varepsilon_{effo}} - \sqrt{\varepsilon_{effe}} \right) \Big/ cZ_{oe} \right] \times l \tag{2}$$

where C_{comp} is the first order estimate for the compensation capacitance to ground.

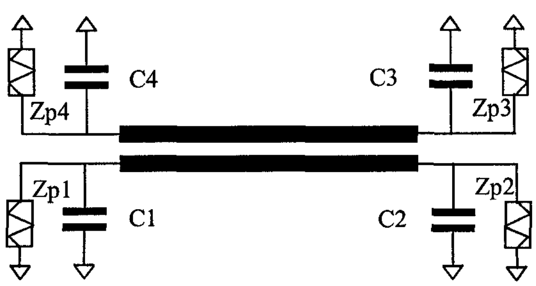


Figure 2. Circuit diagram of proposed topology.

C. *Extracting Normal Mode Parameters from S-Parameters*

To utilize expression (2) we would require an estimate of the normal mode parameters. In this section we derive a set of expression that extract the normal mode parameters from the S-parameters of a four-port network. Starting with the ABCD matrices for the two normal modes we can derive the following expressions:

$$a = \frac{-j(S_{11}+S_{41})}{(S_{21}+S_{31})\sin\beta_e l} \pm \sqrt{1 - \frac{(S_{11}+S_{41})^2}{(S_{21}+S_{31})^2 \sin^2\beta_e l}} \tag{3}$$

$$b = \frac{-j(S_{11}-S_{41})}{(S_{21}-S_{31})\sin\beta_o l} \pm \sqrt{1 - \frac{(S_{11}-S_{41})^2}{(S_{21}-S_{31})^2 \sin^2\beta_o l}} \tag{4}$$

Where $a = Z_{oe}/Z_o$ and $b = Z_{oo}/Z_o$

$$\beta_e = \frac{2}{l}\tan^{-1}\left\{ real\left[\frac{j(S_{21}+S_{31})(a^2+1)}{2a[1+(S_{21}+S_{31})]} \left[1 \pm \sqrt{1 + \frac{4a^2[1-(S_{21}+S_{31})^2]}{(S_{21}+S_{31})^2(a^2+1)^2}} \right] \right] \right\} \tag{5}$$

$$\beta_o = \frac{2}{l}\tan^{-1}\left\{ real\left[\frac{j(S_{21}-S_{31})(b^2+1)}{2b[1+(S_{21}-S_{31})]} \left[1 \pm \sqrt{1 + \frac{4b^2[1-(S_{21}-S_{31})^2]}{(S_{21}-S_{31})^2(b^2+1)^2}} \right] \right] \right\} \tag{6}$$

Where β_e and β_o are the even and odd propagation constant respectively. Note that ε_{effe} and ε_{effo} are given by:

$$\varepsilon_{effe} = \frac{c\beta_e}{2\pi f_o} \tag{7}$$

$$\varepsilon_{effo} = \frac{c\beta_o}{2\pi f_o} \tag{8}$$

The above expressions are not in closed form, therefore we need to solve them by iteration. The first order approximation for the above expressions can be written down as:

$$a = \frac{1 \pm \sqrt{1-4(s_{21}+s_{31}/-2j)^2}}{2(s_{21}+s_{31}/-2j)} \quad (9)$$

$$b = \frac{1 \pm \sqrt{1-4(s_{21}-s_{31}/-2j)^2}}{2(s_{21}-s_{31}/-2j)} \quad (10)$$

Using (9) and (10) as the initial values we iterate using (3)-(6) until we get a convergent solution.

Since we've expressed the normal mode parameters in terms of S-parameters, we can now evaluate the effective impedance and propagation constant of the compensated coupled structure in order to achieve an optimized result.

II. DESIGN EXAMPLE

A. Design Example Using Ideal Model

The use of the developed principles will be demonstrated via a design example using the Libra model CLINP of an inhomogeneous-coupled line. Simulating the model with Input Zoe=120.7, Zoo=20.61, Ke=5.5, Ko=7.8, and Ae=Ao=0 achieved the uncompensated result shown in Figure 3. As can be seen the Isolation of such a coupler is about 24 dB. Applying expression (2) yields the result $C_{comp} = 0.2$ pF for a length l=16100 um. Introducing shunt capacitors to ground at all four ports, as shown in figure 2, with the value 0.2pF, yielded the result shown in Figure 3. Analyzing the S-parameters using (3)-(10) produced effective normal mode parameters of value Zoe=120.4, Zoo=20.7, $\varepsilon_{effe} = 7.8$ and $\varepsilon_{effo} = 8.2$, at the central frequency of 1.8GHz. The first estimate of the equalizing capacitors to ground generated a good improvement, with isolation being better than 38 dB. Optimizing the value of C_{comp} to $C_{comp} = 0.24$ pF resulted in what is also shown in Figure 3. Applying (3)-(10) once again reveals the normal mode parameters to be Zoe=121.2, Zoo=20.8, $\varepsilon_{effe} = 8.3$ and $\varepsilon_{effo} = 8.3$. As we can see the phase velocities have been successfully equated. The isolation at the central frequency has become better than 60 dB.

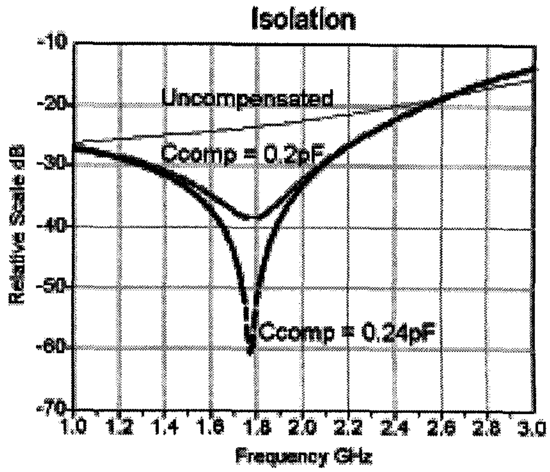


Figure 3. Results of uncompensated, compensated by first order result, and Optimized compensation

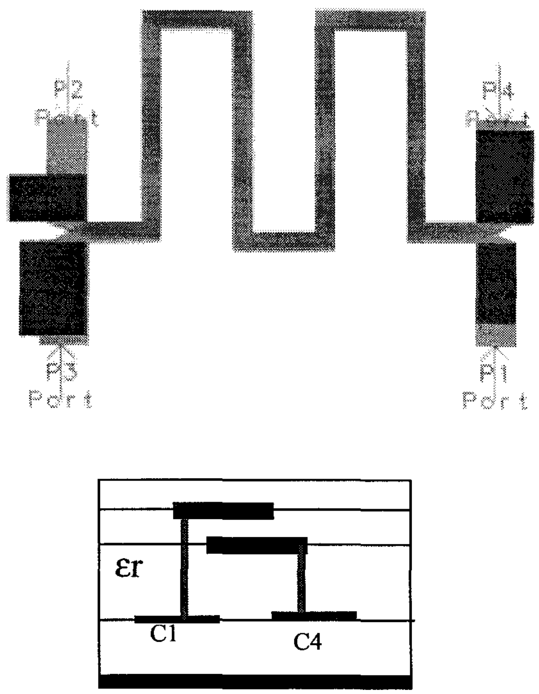
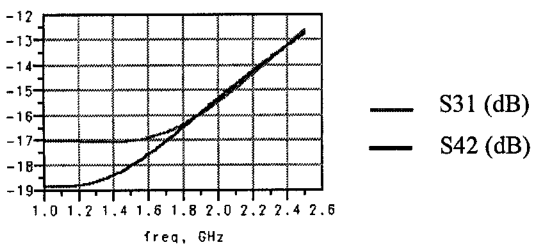


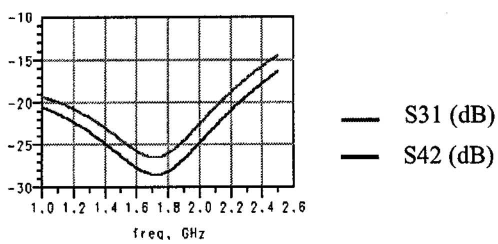
Figure 4. Layout of implemented Coupler with capacitors to ground.

B. Design Example of Practical Structure

Repeating the procedure with a practical embedded broadside-coupled structure on LTCC substrate yielded promising results. Figure 4 shows the layout of a meandered broadside-coupled structure that was implemented on LTCC substrate. The coupler is buried one metalization layer down in a substrate of height 720 um and $\varepsilon_r = 7.8$. This design was implemented and subsequently measured with the measured results seen in Figure 5. The design produced an improved result for the isolation. Further improvement is possible with more careful design of capacitors within manufacturing tolerances. C1 and C2 (Capacitors at port 1and 2 respectively) were designed to exhibit a value of 0.4pF and C3 and C4 were designed for 0.8pF. With the use of Electromagnetic Simulation it is possible to optimize the design for differing capacitor values at each port, producing a more improved response.



(a)



(b)

Figure 5. Measured Isolation of preliminary designs, (a) uncompensated, (b) compensated with capacitors to ground.

V. Conclusion

Broadside microstrip coupled structures on multilayer substrate technologies has been shown to suffer from poor directivity. Using a novel compensation technique as outlined in this paper enables us to realize very high directivity at the central frequency. This allows high performance, cost effective, and miniaturized hybrids to be implemented in microstrip embedded within a multilayer substrate. The methodology is simple and definable with design expressions. Such an approach is highly desirable for high levels of integration of embedded passive components on MCMs. We've demonstrated the principle with a simple design example involving idealized models, and measurements of preliminary fabricated designs have also been presented. Preliminary designs that have been measured show promising results.

References

[1] Donald D. Paolino. "MIC Overlay Coupler Design Using Spectral Domain Techniques", *IEEE Transactions Microwave Theory and Techniques*, vol. MTT-26, no. 9, pp. 646-649, September 1978.

[2] Steven L. March. "Phase Velocity Compensation in Parallel-Coupled Microstrip", *1982 IEEE MTT-S International Microwave Symposium Digest*, pp. 410-412, June 1982.

[3] Alan Podell. "A High Directivity Microstrip Coupler Technique", *1970 IEEE MTT-S International Microwave Symposium Digest*, pp. 33-36, May 1970.

[4] Michael Dydyk. "Microstrip Directional Couplers with Ideal Performance via Single-Element Compensation", *IEEE Transactions Microwave Theory and Techniques*, vol. MTT-47, no. 6, pp. 956-964, June 1999.

[5] I. Toyoda, T. Hirota, T. Hiraoka, T. Tokumitsu. "Multilayer MMIC Branch-Line Coupler and Broad-Side Coupler", 1992 *IEEE Microwave and Millimeter-Wave Monolithic Circuit Symposium*, pp. 79-82, June 1992.

[6] Yasuhiro Fujiki, Harufumi Mandai, Takehiko Marikawa. "Chip Type Spiral Broadside Coupler Directional Couplers and Baluns Using Low Temperature Co-fired Ceramic", 1999 Electronic Components and Technology Conference, pp105-110.

[7] Mark D. Prouty, S.E. Swchwarz. "Hybrid Couplers in Bilevel Microstrip", *IEEE Transactions Microwave Theory and Techniques*, vol. MTT-41, no. 11, pp. 1939-1944, November 1993.

[8] Thomas G. Bryant, Jerald A. Weiss. "Parameters of Microstrip Transmission Lines of Coupled Pairs of Microstrip Lines", *IEEE Transactions Microwave Theory and Techniques*, vol. MTT-16, no. 12, pp. 1021-1027, December 1968.

[9] Rajesh Mongia, Inder Bahl, Prakash Bhartia. "RF and Microwave Coupled-Line Circuits", Artech House, pp.75-79

[10] International Patent application filed on 02.28.2001.