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Microstrip Coupling Algorithm Validation and Modification Based on Measurements and Numerical Modeling

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Abstract: In this study, mutual capacitance and inductance between two coupled traces is measured and computed to validate and simplify coupling algorithms used in an expert system software package. The algorithm's applicability to common microstrip configurations is tested through comparisons between FEM based solutions, S_{21} measurements and the algorithm solutions under several permutations of a test board. Adjustments to the original algorithm are proposed that reduce computation times with out significantly affecting the accuracy of the result.

I. Introduction

EMI and signal integrity software often use mutual capacitance and mutual inductance parameters to calculate the crosstalk between microstrip lines. One set of closed-form equations that is used to solve for these parameters is well established and considered highly accurate [1]. Approximately thirty equations are used to determine even and odd-mode propagation parameters and ultimately the mutual inductance and mutual capacitance values. However, the ability of these equations to calculate parameters for non-ideal PCB configurations with finite ground planes and gapped ground planes has not previously been explored. In addition, these closed-form expressions are cumbersome and require large amounts of computation time.

A sample cross-section of coupled microstrip lines is illustrated in Figure 1. The parameters S, h and W are the edge-to-edge distance between traces, the height of the traces above the ground plane and the width of each trace respectively. The ranges of values for which the equations produce accurate results are given as [1]:

$$.1\le\frac{S}{h}\le 10 \quad .1\le\frac{W}{h}\le 10 \quad 1\le\varepsilon_r\le 18 \tag{1}$$

The derivation of the equations under study assumes that there is an infinite return plane beneath the traces. In addition, the effect of a gap between the coupled microstrips on the accuracy of these equations is not known.

This paper first validates the existing equations, then explores ways the current set of equations can be simplified without losing too much accuracy. Next, the effects of a finite-sized ground plane on the coupling parameters are explored and the effects of a gap in the ground plane between the microstrip trace pair are examined.

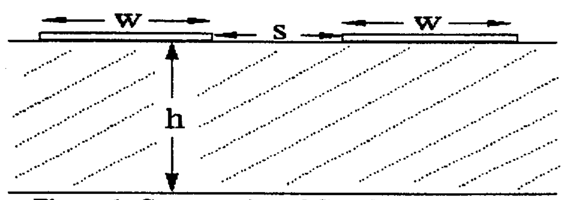

Figure 1: Cross-section of Coupled Microstrips

II. Algorithm Validation

The test circuit used for the laboratory measurements is illustrated in Figure 2. Each test board had four SMA connectors in identical locations and each board included a pair of parallel microstrip traces. The microstrip traces on each board were 0.114 cm (45 mils) wide, and 1.25 mils thick. The dielectric substrate was 0.114 cm (45 mils) thick with a solid ground plane on the other side. Test boards with trace separation values of 0.762 cm (S/h=6.67), 0.457 cm (S/h=4) and 0.114 cm (S/h=1) were used. A network analyzer was used to measure the S_{21} parameter of the each board by connecting Port 1 to one end of one microstrip trace and connecting Port 2 alternatively to the near end and far end of the other microstrip trace. For mutual capacitance measurements, both microstrips were terminated with an open circuit so that electric field coupling would dominate. For mutual inductance measurements, both microstrips were terminated with a short to enhance the magnetic field coupling. Near and far-port crosstalk measurements were made from .1 MHz to 1 GHz. The results are plotted in Figure 3 and Figure 4.

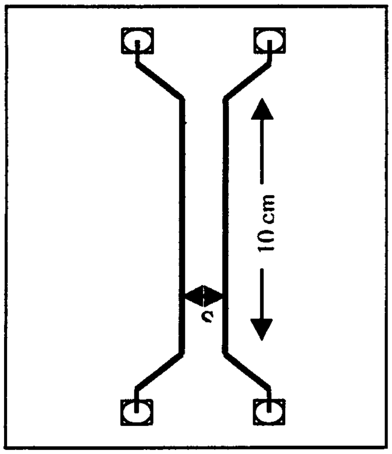

Figure 2: Test board geometry

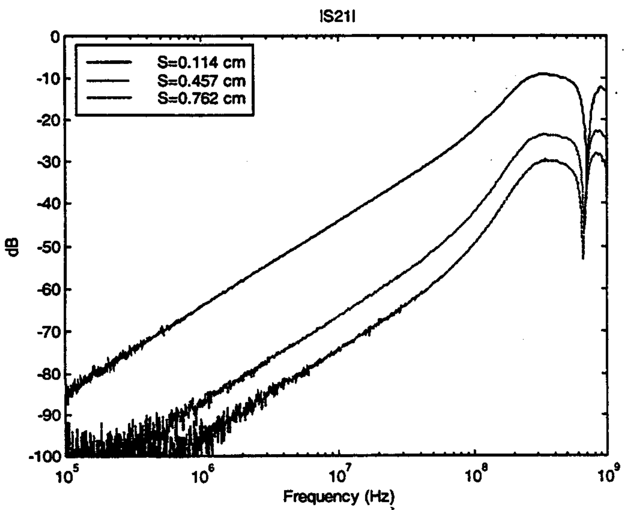

Figure 3: S_{21} Measurement of Mutual Capacitance

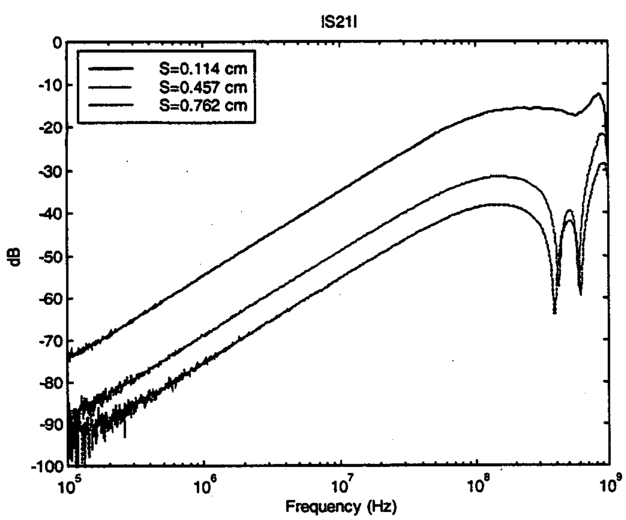

Figure 4: S_{21} Measurement of Mutual Inductance

The mutual capacitance and mutual inductance can then be determined from S_{21} [2] as:

$$C_m := \frac{|S_{21}|}{2 \cdot \omega \cdot Z_L \cdot \text{length}} \tag{2}$$

$$L_m := \frac{|S_{21}| \cdot Z_L}{2 \cdot \omega \cdot \text{length}} \tag{3}$$

assuming,

$$\left| \frac{1}{\omega \cdot C_m} \right| < Z_L = 50 \Omega \tag{4}$$

where Z_L is the port impedance of the network analyzer and 'length' is the coupling length of the microstrip trace pair. In order to obtain the most accurate value for mutual coupling parameters, S_{21} values were taken from the linear part of the S_{21} plots.

It should be noted that the measured S_{21} increased at 20dB per decade. This corresponds to having only one coupling mechanism, mutual capacitance or mutual inductance, between the microstrip pair.

To provide another reference point, test configurations of interest were modeled using a commercially available 2-D FEM code developed by Ansoft. The FEM code included an adaptive meshing algorithm that refined the mesh based on a total energy error calculation. For all FEM simulations, meshes were refined until an energy error less than 0.01% was obtained. An example of an adaptive mesh generated by the FEM code is shown in Figure 5.

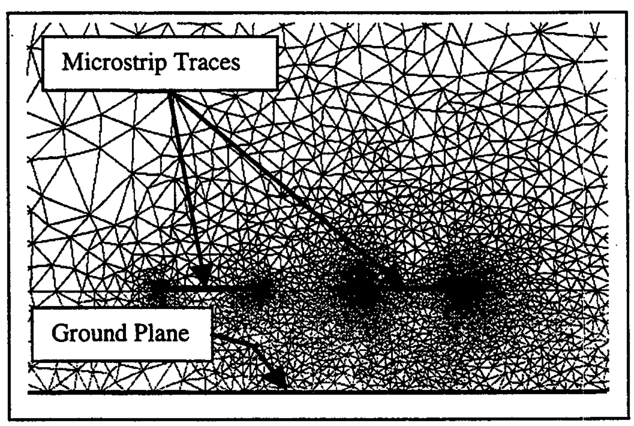

Figure 5: Close-up view of meshing

Solutions calculated using the FEM code, measurements and the analytical equations are summarized in Table 1.

Table 1 FEM, Measurement, and Analytic Results

	FEM Code	Measured Results	Analytic Eqns	% Difference of Eqns vs. FEM & Meas	
				FEM	Meas
S/h=1					
Cm (pF/m)	9.185	9.521	8.997	-2.1%	-5.5%
Lm(nH/m)	78.101	70.866	76.60	-1.9%	-8%
S/h=4					
Cm (pF/m)	.7289	.706	.565	-22%	-20%
Lm (nH/m)	15.664	13.9	14.939	-4.8%	7.5%
S/h=6.67					
Cm (pF/m)	.2595	.272	.223	-14%	-18%
Lm (nH/m)	6.896	6.36	6.04	-12%	-5%

The data in Table 1 shows that the solutions from the FEM code and the measurement results agree very well. The maximum error is 22%, which translates to a field coupling error of less than 2.3 dB..

III. Algorithm Simplification

The mutual-coupling-parameters algorithm is used in an expert system software package to estimate the coupling between high-speed signal traces and I/O lines leaving a PCB. An estimate for the magnitude of the electric field radiated from the I/O trace is then computed. Because the final result is only an estimate, a highly accurate value for the mutual coupling parameters is not required.

In their present form, the equations used to find the mutual-coupling parameters consume significant computation time. Simplifying these equations could save valuable computational resources.

The existing algorithm is valid for microstrips satisfying the following geometric constraints:

$$.1\le\frac{S}{h}\le 10 \quad .1\le\frac{W}{h}\le 10 \quad 1\le\varepsilon_r\le 18 \tag{5}$$

where

$$u:=\frac{S}{h}\ ,\quad g:=\frac{W}{h} \tag{6}$$

To find which equations of the algorithm could be modified, a computer-based numerical tool was used to evaluate each equation over the entire possible range of values of u and g. Plotting each equation as a function of u and g revealed which equations change the least and therefore could be modified. For example, the algorithm calculates the effective dielectric constant as:

$$\varepsilon_{re}:=\frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\cdot\left(1+\frac{10}{u}\right)^{-b\cdot a} \tag{7}$$

where

$$a:=1+\frac{1}{49}\cdot\ln\left[\frac{u^4+\left(\frac{u}{52}\right)^2}{u^4+.432}\right]+\frac{1}{18.7}\cdot\ln\left[1+\left(\frac{u}{18.1}\right)^3\right] \tag{8}$$

$$b:=.564\left(\frac{\varepsilon_r-.9}{\varepsilon_r+3}\right)^{.053} \tag{9}$$

Over the entire range of u, g, and ε_r, the product a·b is constrained to:

$$.385\le a\cdot b\le .563 \tag{10}$$

Simplifying the equation, by setting a·b = 0.5, the equation for the effective dielectric becomes:

$$\varepsilon_{re}:=\frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\cdot\left(1+\frac{10}{u}\right)^{-0.5} \tag{11}$$

Using a similar approach, the equation that calculates the even-mode dielectric constant, ε_{ere}, can be simplified by replacing $a_e\cdot b_e$ with 0.5 to give:

$$\varepsilon_{ere}:=\frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}\cdot\left(1+\frac{10}{v}\right)^{-0.5} \tag{12}$$

where v is given by:

$$v:=u\cdot\frac{20+g^2}{10+g^2}+g\cdot\exp(-g) \tag{13}$$

Other equations can be simplified, including the quantity f, which is used to calculate the characteristic impedance Z_{a0}.

$$Z_{a0}:=\frac{120\pi}{2\cdot\pi}\cdot\ln\left[\frac{f}{u}+\sqrt{1+\left(\frac{2}{u}\right)^2}\right] \tag{14}$$

$$f:=6+(2\cdot\pi-6)\cdot\exp\left[-\left(\frac{30.666}{u}\right)^{.7528}\right] \tag{15}$$

Over the entire range of u and g, the equation for f is contained in the range:

$$6\le f\le 6.027 \tag{16}$$

so f was set equal to 6.0 in the simplified algorithm.

The coupling parameters for several values of u and g after these changes to the algorithm were made are compared to the values from the original algorithm. The comparisons are given in Table 2.

Table 2: Comparisons between the original algorithm and the simplified algorithm

S/h	W/h	C_m (pF/m)		% Diff
		Original	Simplified	
1	**10**	13.54	13.42	-0.9%
1	**7**	12.65	12.70	+0.4%
1	**3**	10.89	10.81	-0.7%
1	**0.1**	4.25	4.03	-5.0%
1	1	8.99	8.716	-3.1%
0.1	1	41.25	40.94	-0.7%
3	1	1.177	0.995	-15.5%
7	1	0.211	0.153	-27%
10	1	0.151	0.125	-17%

From the data in Table 2, the simplified algorithm compares well with the original algorithm. Excluding the data for S/h>3, W/h=1, the simplified algorithm calculates mutual capacitance within 5% of what the original set of equations calculate. When S/h>3, the percent difference is higher, but the coupling is weak for large separations. The maximum 27% error at S/h=7 is comparable to the agreement between the analytical expression and measurements. The mutual inductance did not change in all cases.

IV. Effects of a Finite Ground Plane

The effect of a finite ground plane on the mutual capacitance parameters was measured by changing the extent of the ground plane on a test board. To verify the measurements, FEM simulations were run for each ground plane width measured.

The width of the ground plane on a test board was varied from 23.5 cm to 0.54 cm. A microstrip trace pair with S=0.457 cm, h=0.1143 cm, W=0.1143 cm, and ε_r=4.5 was centered on the varying width ground plane. S_{21} measurements for each ground plane width, GW, are shown in Figure 6 and Figure 7. FEM-based solutions are compared to measured values of mutual capacitance in Table 3.

The width of the ground plane has very little effect on the coupling when the ground plane width is much larger than the separation or trace width.

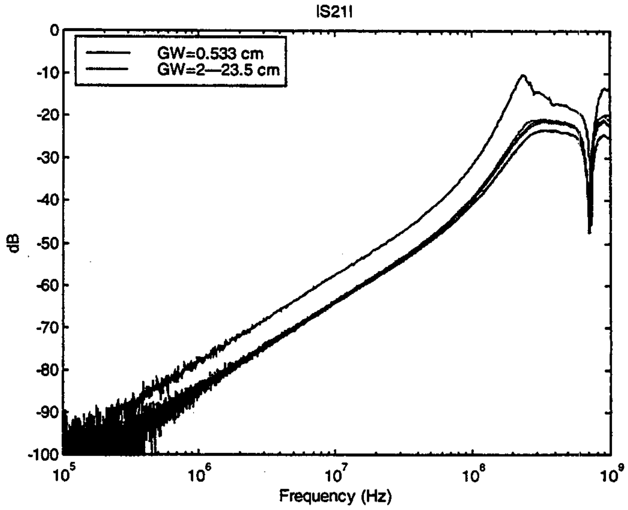

Figure 6: S_{21} measurements for ground plane experiment

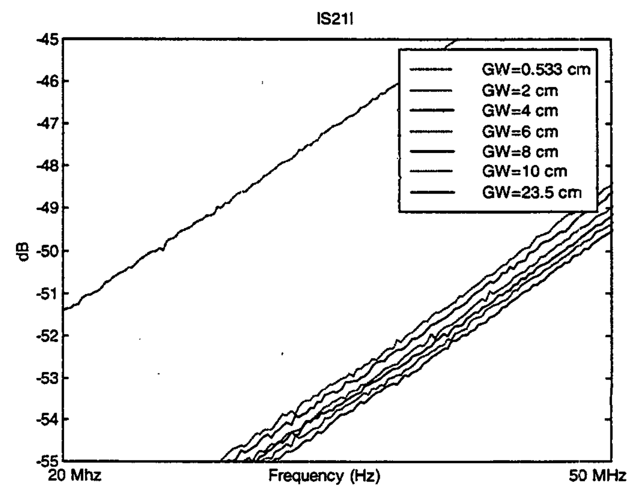

Figure 7: Close-up view of S_{21} measurements for the ground plane experiment

Table 3: Measured and FEM-based solutions for mutual capacitance for different ground plane widths

Ground plane width	C_m (pF/m) ((*Analytical Soln: .565 pF/m*))	
	Measurements	FEM Solution
23.5 cm	0.86	0.73
10 cm	0.98	0.73
8 cm	1.00	0.73
6 cm	1.01	0.73
4 cm	1.03	0.75
2 cm	1.03	0.77
1 cm	--	1.03
0.686 cm	--	1.74
0.546 cm	6.39	2.11

V. Effects of a Gapped Ground Plane

To measure the effects of a gapped ground plane on crosstalk, a gap was cut in the ground plane parallel to and between both microstrips. The width of the gap was varied from 0 to 0.546 cm. The test circuit used for this measurement had the following parameters: S=0.457 cm, h=0.114 cm, W=0.114 cm, and ε_r=4.5. Each trace was terminated with an open circuit so that electric field coupling would dominate.

The S_{21} crosstalk measurements are shown in Figure 8. FEM solutions are compared to measurements in Table 4. From the data provided in Table 4, it should be noted that gapping the ground planes between two microstrip traces does not isolate the traces. Rather, introducing this gap in the ground plane increases mutual coupling. For the configuration tested, gap widths less than 0.1 cm, did not significantly affect the mutual capacitance between the traces. When the gap width was comparable to the trace separation, the mutual capacitance was considerably higher.

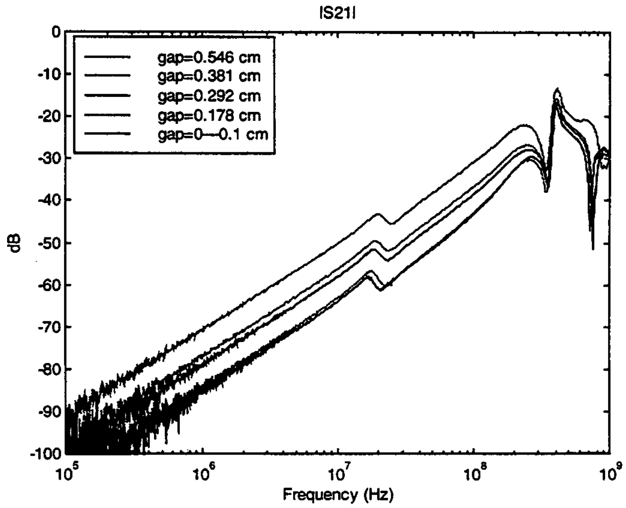

Figure 8: S_{21} measurements for different gap sizes

Table 4: FEM-based solutions and measured values for mutual capacitance with a gap in the ground plane

Gap Width	C_m (pF/m) ((*Analytical Solution: .565 pF/m*))	
	Measurements	FEM Solution
0.546 cm	4.84	4.63
0.381 cm	2.43	2.11
0.292 cm	1.96	1.35
0.229 cm	--	1.05
0.178 cm	1.10	0.90
0.100 cm	1.00	0.77
0.051 cm	--	0.74
0 cm	0.86	0.73

VI. Conclusions

An algorithm that calculates mutual coupling parameters [1] was validated using an FEM code and laboratory measurements. All three solution methods agreed to within 2.3 dB (max. error: 22%) of one another.

The long and cumbersome equations used in the algorithm were simplified to decrease computation time. The simplified algorithm produced results within 5% of what the original algorithm calculated for most microstrip configurations. For those configurations where the error was more than 5%, the mutual coupling was relatively low and therefore was less significant.

The mutual coupling parameter algorithm assumed an infinite ground plane was positioned beneath both microstrip traces. To observe the effect that a finite-sized ground plane had on the coupling parameters, laboratory measurements were completed and FEM simulations were run for several ground plane widths. The results indicated that the assumption of an infinite ground plane was valid for ground planes larger than approximately twice the trace separation for the particular configuration measured in this paper.

Quite often gaps in the ground plane are used to isolate two traces from one another. However, when a gap was introduced in the ground plane between two microstrip traces, measurements and simulations indicated that the mutual coupling parameters increased.

References

[1] K. C. Gupta, Ramesh Garg, Inder Bahl and Prakash Bhartia, *Microstrip Lines and Slotlines*, Second Edition, Artech House, Inc., Norword, Massachusetts, 1996.

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