ANALYSIS OF GROUND BOND WIRE ARRAYS FOR RFICS

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Abstract

This paper outlines a method for rapid computation of the inductance of arrays of ground bond wires for RFICs, thus saving a designer considerable time over using inaccurate empirical equations or slowly converging electromagnetic simulators. Results comparable in accuracy to a fully detailed PEEC electromagnetic simulation are shown.

Introduction

Bond wires which connect the grounds of RFICs to the package or system ground have a large effect on circuit gain, efficiency, and stability because of the inductance they add into the common leads. In an attempt to reduce this inductance, they are often paralleled as is shown in Figure 1 to form an array. It is important for a designer to be able to compute the total inductance of a bond wire array in order to place the correct value in a simulator to predict final circuit performance. The inductance of arrays of bond wires is often calculated with equations derived for straightened wires or with complex, time consuming electromagnetic simulations. For curved wires over a ground plane, magnetic couplings exist within a single wire, between wires, between wires and their ground plane images, and between wires and the ground plane images of other wires in a complex web. Simple models neglect these effects and lose considerable accuracy as a result.

This paper outlines a quick method of computing the inductance of wire bond arrays which accounts for many of the effects described above and which has accuracies approaching detailed electromagnetic simulation. Although the equations presented here are complex, they are straightforward to program and can give results in seconds compared to hours for electromagnetic simulation. The optimum number of wires, lengths, and spacings to achieve a particular inductance can easily be found or an existing array can be analyzed for its parasitics.

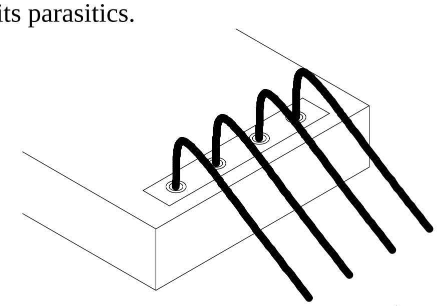

Figure 1: Typical Ground Bond Wire Configuration

Outline of the Method

In the configuration of Figure 1, the chip sits on a conductive, grounded surface and wires are bonded between pads on the chip and ground. The wires in this instance are ball bonded with the ball on the chip, a common method of realizing ground bonds in volume manufacturing.

The geometry of a single bond is shown in Figure 2. The bond rises straight up above the ball a short distance, then bends over and runs into ground at an angle θ. The distance from the chip to the grounding point is often tens of mils to avoid the solder or epoxy fillet which is usually present around the bottom of the chip. This is the geometry analyzed in this paper. It is assumed that all the wires in the array are of identical shape and size.

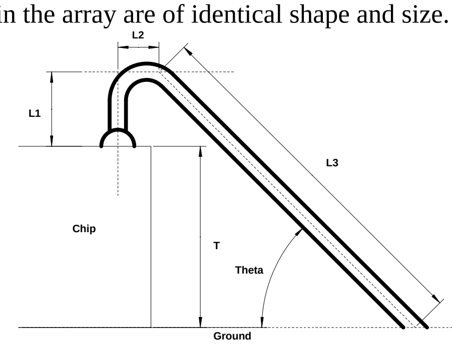

Figure 2: Typical Bond Wire Configuration

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In order to simplify calculations, the wire is approximated as three straight sections, illustrated in Figure 3. Section 1 bisects the center of the vertical part of the bond and extends up far enough to intersect a line drawn through the center of the horizontal part of the wire. Section 2 connects section 1 and the center of the angled part of the wire. Section 3 connects ground to section 2 by a straight line drawn through the center of the angled part of the wire. A typical bond wire can be measured under a microscope to come up with the best fit lengths and angles for each section. A thin filament is imagined through the center of each section for mutual inductance calculations. t in Figure 3 is the thickness of the die.

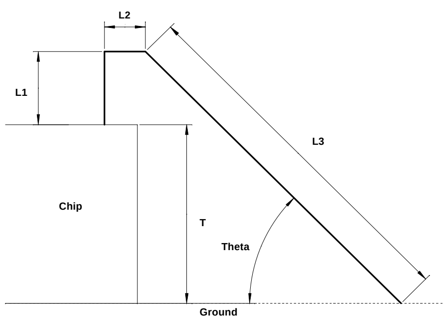

Figure 3: Approximating Filaments for Single Wire Bond

All of the following equations were adapted from Reference [1].

The self inductance of each segment is calculated by using an equation for the inductance of a straight, finite diameter wire. The total inductance in nH is given by applying this equation to all segments and summing

$$\Lambda_{123} = \sum_{k=1}^{3} 5.08 \cdot l_k \cdot \left(\ln\left(\frac{4 \cdot l_k}{d_w} \right) - 1 + \frac{T}{4} \right) \qquad (1)$$

where T is a correction factor given by (2) to account for skin effect with f in GHz, d_w is the wire diameter in inches, and l_k the length of segment k in inches.

$$T = \frac{.93736 + 5.04858 \cdot 10^{-2} \cdot d_w \cdot \sqrt{f}}{1 + 4.13946 \cdot 10^{-3} \cdot d_w \cdot \sqrt{f} + 6.48192 \cdot 10^{-3} \cdot d_w^{2} \cdot f} + 6.3 \cdot 10^{-2} \cdot e^{\left(-2.72034 \cdot d_w \cdot \sqrt{f}\right)} \qquad (2)$$

Six mutual inductances must be calculated in addition to the self inductance of the wire. Using the section numbers as subscripts, mutual inductances within the wire are M_{13} and M_{23} while mutual inductances to the ground plane image sections are $M_{22`}$, $M_{33`}$, $M_{13`}$, and $M_{23`}$ with the primed subscript referring to the image of each segment in the ground plane.

$M_{22`}$ in nH is given by

$$M_{22'} = 5.08 \cdot L_2 \cdot \left[\ln\left[\frac{L_2}{(t + L_1)} + \sqrt{1 + \frac{L_2^{2}}{(t + L_1)^2}} \right] - \sqrt{1 + \frac{(t + L_1)^2}{L_2^{2}}} + \frac{(t + L_1)}{L_2} \right] \qquad (3)$$

where t is the die thickness and L_n are the lengths of the segments.

$M_{33`}$ in nH is given by

$$M_{33'} = 5.08 \cdot L_3 \cdot \cos(\theta) \cdot \left(-\sqrt{1 + \tan(\theta)^2} + \ln\left(\cot(\theta) + \sqrt{1 + \cot(\theta)^2} \right) + \tan(\theta) \right) \qquad (4)$$

where L_3 is the length of segment 3 and θ is the angle with ground. This is a modification of (3) to account for coupling to surface currents on the ground plane.

M_{23} in nH is given by

$$M_{23} = -5.08 \cdot \cos(\theta) \cdot \left(L_2 \cdot \operatorname{atanh}\left(\frac{L_3}{L_2 + R} \right) + L_3 \cdot \operatorname{atanh}\left(\frac{L_2}{L_3 + R} \right) \right) \qquad (5)$$

where

$$R = L_2 \cdot \sqrt{1 + \frac{L_3^{2}}{L_2^{2}} + 2 \cdot \frac{L_3}{L_2} \cdot \cos(\theta)} \qquad (6)$$

M_{13} in nH is calculated from

$$M_{13} = 5.08 \cdot \sin(\theta) \cdot \left[-\mu \cdot \operatorname{atanh}\left(\frac{L_1}{R_3 + R_4} \right) - \nu \cdot \operatorname{atanh}\left(\frac{L_3}{R_2 + R_3} \right) + (\mu + L_3) \cdot \operatorname{atanh}\left(\frac{L_1}{R_1 + R_2} \right) + (\nu + L_1) \cdot \operatorname{atanh}\left(\frac{L_3}{R_1 + R_4} \right) \right] \qquad (7)$$

where

$$\nu = (t + L_1 + L_3 \cdot \cos(\theta)) \cdot \tan(\theta) - t - L_1 \qquad (8)$$

and

$$\mu = \frac{t + L_1 + L_3 \cdot \cos(\theta)}{\cos(\theta)} - L_3 \qquad (9)$$

with

$$R_1 = \sqrt{(\mu + L_3)^2 + (\nu + L_1)^2 - (2 \cdot \mu + 2 \cdot L_3) \cdot (\nu + L_1) \cdot \sin(\theta)} \qquad (10)$$

$$R_2 = \sqrt{(\mu + L_3)^2 + \nu^2 - 2 \cdot \nu \cdot (\mu + L_3) \cdot \sin(\theta)} \qquad (11)$$

$$R_3 = \sqrt{\mu^2 + \nu^2 - 2 \cdot \mu \cdot \nu \cdot \sin(\theta)} \qquad (12)$$

$$R_4 = \sqrt{\mu^2 + (\nu + L_1)^2 - 2 \cdot \mu \cdot (\nu + L_1) \cdot \sin(\theta)} \qquad (13)$$

$M_{13`}$ is given by

$$M_{13'} = 5.08 \cdot \sin(\theta) \cdot \left[-\mu \cdot \operatorname{atanh}\left(\frac{L_3}{R_3 + R_4}\right) - \nu \cdot \operatorname{atanh}\left(\frac{L_1}{R_2 + R_3}\right) \ldots \right.$$
$$\left. + (\mu + L_1) \cdot \operatorname{atanh}\left(\frac{L_3}{R_1 + R_2}\right) \ldots + (\nu + L_3) \cdot \operatorname{atanh}\left(\frac{L_1}{R_1 + R_4}\right) \right] \quad (14)$$

with

$$\mu = t + (t + L_1) \cdot \frac{L_3 \cdot \sin(\theta) + L_2}{L_3 \cdot \sin(\theta)}, \quad (15)$$

$$\nu = \sqrt{L_2^{\,2} + \left[(t + L_1) \cdot \frac{L_3 \cdot \sin(\theta) + L_2}{L_3 \cdot \sin(\theta)} - t - L_1 \right]^2} \quad (16)$$

where R_1-R_4 are given by (10)-(13) with the values of L_1 and L_3 interchanged.

$M_{23'}$ in nH is given by

$$M_{23'} = 5.08 \cdot \sin(\theta) \cdot \left[-\mu \cdot \operatorname{atanh}\left(\frac{L_3}{R_3 + R_4}\right) - \nu \cdot \operatorname{atanh}\left(\frac{L_2}{R_2 + R_3}\right) \ldots \right.$$
$$\left. + (\mu + L_2) \cdot \operatorname{atanh}\left(\frac{L_3}{R_1 + R_2}\right) \ldots + (\nu + L_3) \cdot \operatorname{atanh}\left(\frac{L_2}{R_1 + R_4}\right) \right] \quad (17)$$

with

$$\mu = 2 \cdot L_3 \cdot \cos(\theta) \quad (18)$$

$$\nu = \frac{2 \cdot (t + L_1) - L_3 \cdot \sin(\theta)}{\sin(\theta)} \quad (19)$$

and R_1-R_4 are given by (10)-(13) with the following changes: L_3 is replaced by L_2, L_1 is replaced by L_3, and the $\sin(\theta)$ terms are replaced by $\cos(\varepsilon)$ where ε is given by

$$\varepsilon = \operatorname{asin}\left[\frac{2 \cdot (t + L_1)}{L_3 + \nu} \right] \quad (20)$$

Once the self and mutual inductances for each segment in a single wire are calculated, they must be properly combined to form the total inductance of the wire. The self inductance of a segmented conductor is the sum of the self inductances of all segments, mutual inductances between a segment and its image in the ground plane, twice the mutual inductances between segments within the wire, and twice the mutual inductance between a segment and ground images of other segments. The factor of 2 is included because there are mutuals in both directions between coupled conductors and both must be included if the conductors share current. In equation form this is written as

$$\Lambda_T = \Lambda_{123} - M_{22'} - 2 \cdot M_{13} - M_{33'} - 2 \cdot M_{23} - 2 \cdot M_{23'} - 2 \cdot M_{13'} \quad (21)$$

with Λ used to symbolize inductance.

The preceding analysis gives the inductance of a single bond wire. To analyze multiple wires, it is necessary to calculate the coupling between a wire and each of the others in the array, along with coupling to the images of the other conductors. This is a complex procedure and must be simplified to give tractable calculations.

Mutual inductance between wires is approximated by assuming that the broadside coupling between identical segments is the only dominant factor. This is a good assumption because the relative spatial orientation of off-broadside segments gives low mutual inductance for this type of wire geometry. The mutual inductance in nH between filaments through the center of each section is given by

$$Mu(l, d) = 5.08 \cdot L \cdot \left[\ln\left[\frac{L}{d} + \sqrt{1 + \left(\frac{L}{d}\right)^2} \right] - \sqrt{1 + \left(\frac{d}{L}\right)^2} + \frac{d}{L} \right] \quad (22)$$

where L is the length of the filaments and d is the perpendicular distance between them. Assuming each wire in the array is separated by a fixed distance s, the off-diagonal elements ($i \neq j$) of the inductance matrix $\boldsymbol{\Lambda}$ can be filled using the following formula

$$Mut_{i,j} = \left[\sum_{k=1}^{3} Mu\left(l_k, s \cdot |j - i|\right) - Mu\left[l_k, \sqrt{(s \cdot (j - i))^2 + [2 \cdot (t + L_1)]^2} \right] \right] \quad (23)$$

which states that the total mutual inductance between a pair of wires is the sum of the mutual inductances between each of the three broadside coupled segments of the two wires minus the mutuals to the ground plane image of each segment. For the main diagonal of $\boldsymbol{\Lambda}$ where i=j, the self inductance of each wire calculated from (21) is inserted.

For a parallel connected array of coupled inductors, the vector of voltages across the inductors is related to the currents in each inductor by

$$\vec{V} = j \cdot \omega \cdot \vec{\Lambda} \cdot \vec{I} \quad (24)$$

Boundary conditions for solving this equation can be identified by recognizing that the bond wires are connected together at each end and so have a common voltage. This voltage can be anything at all and will be conveniently chosen as 1 volt.

$$V_i = 1 \quad (25)$$

Also, the total current flowing into the structure is the sum of the currents in each wire, expressed as

$$I_{tot} = \sum_i I_i \quad (26)$$

Therefore, the total inductance of the wire array is

$$\Lambda_{tot} = \frac{V}{j \cdot \omega \cdot I_{tot}} \quad (27)$$

The array of individual wire currents $\vec{I}$ can then be solved from (24) by using the boundary conditions (25) and (26).

$$\vec{I} = \left(\vec{\Lambda}\right)^{-1} \cdot \frac{1}{j \cdot \omega} \cdot \vec{V} \quad (28)$$

Combining (27) and (28) gives

$$\Lambda_{tot} = \frac{1}{\sum_i \left(\vec{\Lambda}\right)^{-1} \cdot \vec{V}} \quad (29)$$

where $\vec{V}$ is a column matrix of 1's due to the 1 volt boundary condition on each wire.

Comparison To Simulation

Due to the difficulties of accurate measurement of bond wire arrays, the analysis presented in this paper is compared to a known accurate electromagnetic simulation. Calculations of several wire configurations were performed on Pacific Numerix® [2] Parasitic Parameters software using a PEEC technique to compute inductance of the parallel bonds. Parameters of the configurations used are shown in Table 1.

	Wire Length (in)	
	0.034	0.045
Segment 1 Length (in)	0.005	0.005
Segment 2 Length (in)	0.005	0.007
Segment 3 Length (in)	0.024	0.033
Ground Angle (deg)	40	27

Table 1: Wire Parameters Used for Comparison

All wires had a diameter of 1 mil. A chip thickness t of 4 mils was assumed and the frequency was 2 GHz. Calculations were also done using the inductance of a single wire divided by the number of bonds for comparison.

The equations in this paper were programmed into Mathcad® running on a Pentium® PC with a clock speed of 133 MHz. Pacific Numerix® was run on a Sun [3] Ultra 2 SparcStation® with a clock speed of 200 MHz. Arrays of up to three wires only were done on Pacific Numerix® because of computational limitations. For the three bond array, calculations on the PC took 1 second while those on the SparcStation® were completed in 1 hour. Table 2 shows the results.

Number of Bonds	Wire Length (mil)	Distance Between Wires (mil)	Inductance by Method of this Paper (nH)	Inductance from Pacific Numerix (nH)	Inductance from Total Wire Length Method (nH)
1	34	-	0.49	0.46	0.73
1	45	-	0.67	0.67	0.98
2	34	2	0.39	0.36	0.36
2	34	6	0.31	0.30	0.36
2	34	15	0.27	0.26	0.36
2	45	2	0.54	0.53	0.49
2	45	6	0.44	0.44	0.49
2	45	15	0.37	0.38	0.49
3	45	2	0.46	0.45	0.33
3	45	6	0.34	0.33	0.33
3	45	15	0.26	0.27	0.33

Table 2: Comparison of Wire Inductance by Method of this Paper, Pacific Numerix®, and Total Wire Length Divided by Number of Bonds

In Table 2, column 4 is the inductance computed by the method of this paper, column 5 is the inductance computed from full Pacific Numerix® simulations, and column 5 is the inductance computed from the length of the wire divided by the number of bonds, a common method used by RF designers.

Table 3 shows the percentage errors for each case.

Number of Bonds	Wire Length (mil)	Distance Between Wires (mil)	Percent Error, This Paper to Pacific Numerix	Percent Error, Traditional Method to Pacific Numerix
1	34	-	6.52	36.99
1	45	-	0.00	31.63
2	34	2	8.33	0.00
2	34	6	3.33	16.67
2	34	15	3.85	27.78
2	45	2	1.89	8.16
2	45	6	0.00	10.20
2	45	15	2.63	22.45
3	45	2	2.22	36.36
3	45	6	3.03	0.00
3	45	15	3.70	18.18

Table 3: Percentage Errors Between the Two Methods and Pacific Numerix®

As can be seen, the method of this paper is much more accurate overall than the traditional method which is dependent on the wire configuration.

[1] F. W. Grover, *Inductance Calculations*, New York, Dover Publications, 1962.
[2] Pacific Numerix Corporation, 7333 E. Doubletree Ranch Rd., Suite 280, Scottsdale, AZ 85258
[3] Sun Microsystems, Inc. 2550 Garcia Ave., Mountain View, CA. 94043