

Microwave modelling and measurement of the self- and mutual inductance of coupled bondwires

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Abstract

The modelling and measurement of the self- and mutual inductance of bonding wires up to 10 GHz is considered. Differences less than 10 % between calculated and measured self inductances are reported. The influence of various parameters on the inductance is considered.

1 Introduction

Bondwires are used in both analog and digital integrated circuits to interconnect IC's and packages. The accurate electrical modelling of bondwires has become an important issue due to increasing frequencies in these integrated circuits. The electrical behaviour of bondwires is predominantly inductive and quite often a rule of thumb based on the geometrical length of the wire, is used to estimate the inductance. An improvement can be made if closed form equations are used to compute the self- and mutual inductance of wires [1]. In critical applications, however, these rules fail to predict the inductance accurately. Such a case occurs for example if the wire is close to a ground plane or if the wire has (sharp) bends in it.

In this paper we consider the modelling of bondwires based on the geometry of the wire and Neumann's inductance equation. Microwave measurements, spanning the 45 MHz to 10 GHz range, are performed on sets of coupled bondwires with differing wire lengths and differing spacings between the wire in order to verify the assumptions made in the modelling.

Differences less than 10 % between the calculated self-inductances and the measurements have been found.

Larger differences are found for the mutual inductance in case of loose coupling. Several causes for the differences are discussed.

2 Set-up of the geometrical and microwave measurements

The measurement of the bondwires proceeds in two steps. First the geometrical dimensions, needed to calculate the bondwire inductance, are measured from photographs made of the bondwires. In the second step the reflection parameters S_{11} and S_{22} and the transmission parameters S_{21} and S_{12} are measured between 45 MHz and 10 GHz. The inductances

are extracted from the measured data. Both measurements are discussed in the following.

2.1 Geometrical measurements

To calculate the self and mutual inductances of bondwires the geometry of the coupled wires must be known. To that end, a top view photo and two side view photo's are made of each pair of bondwires with a SEM. An example of these photo's is shown in figure 1.

Relevant dimensions are indicated in the top view of the bondwire setup of figure 2.

In this figure a coplanar transmission line, with length L , width W and spacing S is shown. The length of the line is made 200 μm . This length of the line is a compromise between the shortest line possible and the minimum length needed for a correct bonding. The width and spacing of the line are chosen equal to the dimensions of the coplanar probe ($W = 50 \mu\text{m}$ and $S = 50 \mu\text{m}$).

Two sets of bondwires, with differing horizontal lengths LH_w and different wire spacing S_w are considered. The first set of 5 bondwires have a horizontal length of approximately 500 μm and a spacing between the bondwires of 1000 μm , 1000 μm , 900 μm , 800 μm and 700 μm respectively. The second set of 4 bondwires have a horizontal length of 1000 μm and a spacing between the wires of 600 μm , 500 μm , 400 μm and 200 μm . In both sets of bondwires the height of the wires above the ground plane is approximately 200 μm and the wire radius 19 μm .

The interconnect length from the probe to the bondwire, indicated by L_d , is also measured from the photographs. Please note that this length must be measured for each wire because the wires are not bonded at exactly the same position along the interconnect; variations are in the order of 30 μm . The overtravel distance of the microwave probe is 40 μm (see figure 2).

2.2 Microwave measurements

The bondwires were measured with a HP8517A vector network analyser system in the frequency range of 45 MHz to 10 GHz. The lines are probed using a Cascade Microtech GSG wafer probe with 100 μm pitch. It was found that the self inductance, extracted on the basis of an inductance-resistance model, can vary in the order of 10 to 15 pH in this frequency range.

3 Inductance modelling

Two methods were used to obtain the inductance of the bondwire:

- In the first the geometry of the wire is measured from photo's made from each wire. The geometrical data is then used in Neumann's inductance formula to calculate the self- and mutual inductances of the wires.
- In the second the scattering parameters S_{11} , S_{22} , S_{21} and S_{12} are measured in the frequency range of 45 MHz to 10 GHz and the inductances are extracted from these measurements.

Both points are considered in the following.

3.1 Bond wire inductance modelling

The modelling of the bondwires is based on Neumann's inductance formula for closed loops [2], [3]. Open loops can be treated using the concept of partial inductance [4]. The inductance formula considers two closed loops of thin wires with the contour C_i defining the center of the current carrying wire i and the contour C_j defining the interior edge of closed loop j . The mutual inductance between these two loops is then given by:

$$\begin{aligned} L_{ij} &= \frac{\text{flux linking } C_j \text{ due to a current in } C_i}{\text{current in } C_i} \\ &= \frac{\mu_0}{4\pi} \oint_{C_i} \oint_{C_j} \frac{dl_i \cdot dl_j}{r} \end{aligned} \quad (1)$$

where r is the distance between the points on the contours C_i and C_j . In case of the self inductances L_{11} and L_{22} the first contour is on the center of the wire and the second contour is on the interior edge of the wire [3]. In our application a loop is made by considering the image of the bondwire in the ground plane i.e. the wire is mirrored in the ground plane and the computed inductance for this loop is divided by a factor 2. With the inductance equation of Grover [5] the inductance of a loop is computed by breaking the wire up in a set of straight segments and computing equation (1) on a piece-wise basis.

3.2 Inductance extraction from measurements

The geometrical modelling of the wires based on equation (1) yields a unique value for the inductance. The extraction of inductance values from the scattering parameter data is less straightforward:

1. A model for the measured situation must be chosen.
2. The values of the elements in this model must be extracted from the measurements.

The assumed model for the measured configuration is shown in figure 3. The model for the first wire plus interconnect consists of a capacitance C_{pg} , a transmission line TL_1 , a capacitance C_{wg1} , a self inductance L_{11} and a resistance R_1 . The same circuit is repeated for the next wire. These two

circuits are linked together through the mutual inductances L_{21} and L_{12} . We assume that L_{21} is equal to L_{12} . The capacitance C_{pg} models the capacitance between the small piece of open ended transmission line and the probe to ground. The transmission line models the interconnect line between the probe-tip and the beginning of the bondwire. The length of this line (L_d) is measured from the photographs. The value of C_{pg} (approximately 10 fF) and the transmission line parameters are extracted from measurements on lines with differing lengths. The measurement data can now be de-embedded, removing the transmission lines and the capacitance C_{pg} yielding the input impedance matrix of the reduced network. As a first step we assume the capacitance C_{wg} negligible. This capacitance models the capacitance of the wire to ground and the capacitance of the open end of the coplanar line to ground. The extraction of the resistance and inductance from the impedance matrix is straightforward:

$$R_i = \Re(Z_{ii}) \quad L_{ij} = \frac{\Im(Z_{ij})}{\omega} \quad (2)$$

where $\Re(\cdot)$ and $\Im(\cdot)$ represent the real and imaginary part respectively, $\omega = 2\pi f$ and $i = 1, 2$ and $j = 1, 2$.

Now we add back the wire to ground capacitances C_{wg1} and C_{wg2} . The extraction of the inductances is less straightforward in this case. Suppose that the capacitance C_{wgi} is known. In that case we can de-embed the data for this capacitance and extract the resistance and inductance using equation (2) from the newly calculated impedance matrix. This leaves us with the problem of finding the capacitance. Although an exact equation can be derived to extract the capacitance from the measured data, it proved to be very sensitive to measurement errors. This problem can be avoided if C_{wg} is chosen such that the derivative of the extracted inductance, using equation (2), with respect to frequency is zero:

$$\frac{\partial L_{ij}}{\partial \omega} = 0 \quad (3)$$

It was found that this capacitance is 5-20 fF depending on the exact placement of the bond wire. The main advantage of the model with wire to ground capacitance is that the extracted inductance is less sensitive to de-embedding errors than the model without this capacitance. The difference between self inductance values extracted using models with and without this capacitance is found to be in the order of 10-20 pH.

4 Measurement results

Two different sets of bondwires were measured. The first set of 5 bondwires have a horizontal length of 500 μm and the second set of 4 wires have a length of approximately 1000 μm . Photographs were made of each bondwire and all relevant lengths are measured from these photographs. The scattering parameters of the coupled wires were measured from 45 MHz to 10 GHz. The results of the measurements of the two sets of bondwires are discussed in the following.

4.1 Bondwire $LH_w = 500 \mu\text{m}$

The measured and modelled inductance of the 5 samples with a length of approximately 500 μm are shown in figure

4. From this figure we observe that the measured inductance L_{11} is between 0.33 nH and 0.36 nH and L_{22} between 0.34 and 0.38 nH. The difference between these inductances is due to the longer length of the second wire compared to the first wire. A maximum relative difference between the model and the measurements in the order of 6-8 % has been found for the self inductances.

The mutual inductance is between 2 and 7 pH. Note that the distance between the wires is 1000 μm for samples 1 and 2, 900 μm for sample 3, 800 μm for sample 4 and 700 μm for sample 5. Although both calculation and measurement show the same trend, a maximum difference of 30 % is found for sample 3.

4.2 Bondwire $LH_w = 1000 \mu\text{m}$

The measured and modelled inductance of 4 samples with a length of 1000 μm are shown in figure 5.

From this figure we observe that the measured self inductance is between 0.52 nH and 0.56 nH. The maximum difference between the measured and modelled self inductance is 3 %. The mutual inductance is between 15 pH and 115 pH. Again we find that both the calculation and the measurement show the same trend and in this case the difference between the measured and modelled mutual inductance is much smaller compared with the wires of 500 μm .

5 Discussion

In this section the sensitivity of the extracted inductances to errors in the geometrical and the microwave measurements is considered. As an example, we investigate these sensitivities for a wire with a horizontal length of 500 μm and a spacing between the wires of 900 μm (sample number 3 in figure 4). First the main sensitivities of the self inductances and then the main sensitivities of the mutual inductance are discussed.

5.1 The self inductance

First of all we note that a change of the wire radius of 1 μm gives a change in the inductance of around 2 %. Secondly, an error of 20 μm in the de-embedding length results in an error of 3 % in the inductance. A third cause of error is due to measurement of the geometrical data. If an error of 2 % is made in these lengths, an error of 3 % in inductance is obtained. Finally an error in the phase of the reflection coefficient S_{11} contributes to the error in the measured inductance. If a constant phase error with respect to frequency is assumed, the error in extracted inductance depends on frequency. For example a phase error of 0.5 degrees at 1 GHz results in an error of 10 % in the inductance. The same phase error at 10 GHz gives an error of 1 % in inductance.

5.2 The mutual inductance

The mutual inductance is less sensitive to changes in the wire radius; a change of 1 μm in the radius gives a change of 0.5 % in the inductance. The mutual inductance is also less sensitive to errors in the de-embedding distance. An error of 20 μm in this length results in an error of 0.25 % in

the extracted inductance. A more important cause of error is in the measurement of the geometrical data. An error of 2 % introduces an error of 2 % in the extracted inductance. Finally we consider errors in the scattering parameters. An error of 0.2 dB in the magnitude of the reflection parameters gives an error of 2.5 % in the extracted inductance. The magnitude of the transmission parameters S_{12} and S_{21} is around -50 dB for the 500 μm wires. If an error of 0.5 dB is made in these parameters an error of 6 % in the mutual inductance results. Please note that the wires with a length of 1000 μm have a much higher coupling and, consequently, have a much lower error in the transmission parameters. This explains the relatively small difference between measured and modelled mutual inductance in figure 5.

6 Conclusions

In this paper the modelling and measurement of bond wire inductances is considered. The aim of this study was to compare Neumann's inductance formula with measured self- and mutual inductances at microwave frequencies up to 10 GHz. After de-embedding of the measurement data for parasitic capacitances and the coplanar interconnect line, the self- and mutual inductances are extracted. Two sets of bondwires are considered: the first set of wires have a horizontal length of 500 μm and the second set a length of 1000 μm . Maximum differences of 10 % between measured and modelled self inductances are found. Larger differences are found for the mutual inductances of the 500 μm samples. Finally several causes for these differences are discussed.

7 Acknowledgement

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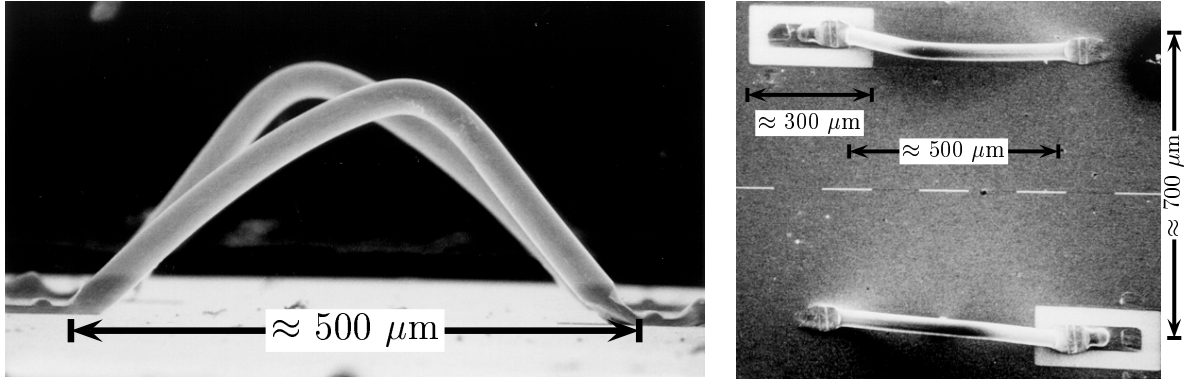


Figure 1: Side view photo and top view photo of a set of two coupled bondwires.

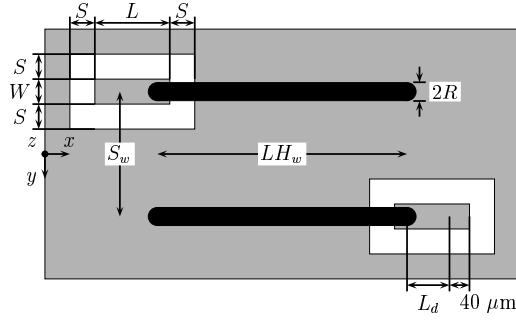


Figure 2: Top view of the coupled wires measurement setup, showing the coplanar interconnects and the wires.

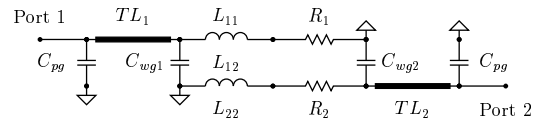


Figure 3: Equivalent circuit for the measurement setup.

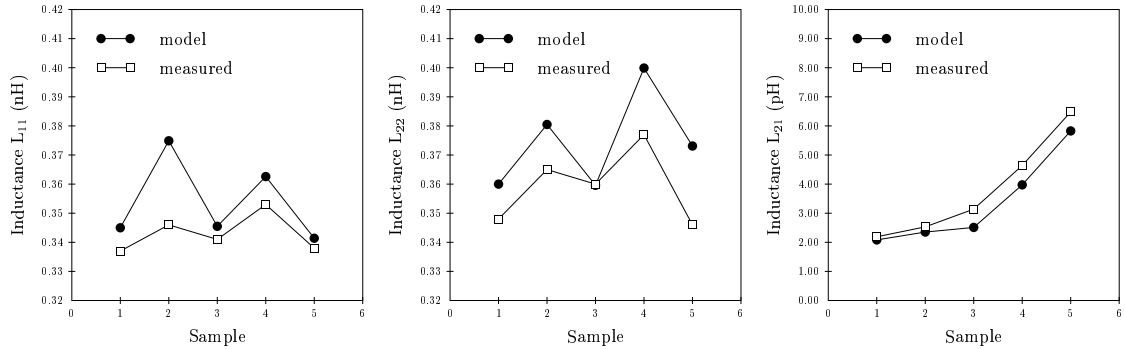


Figure 4: Self inductances L_{11} (shown on the left) and L_{22} (middle) and mutual inductance L_{21} (right) for five sets of coupled wires with a horizontal length LH_w of approximately $500 \mu\text{m}$. The spacing between the wires S_w is 1000, 1000, 900, 800 and $700 \mu\text{m}$ for samples 1-5 respectively.

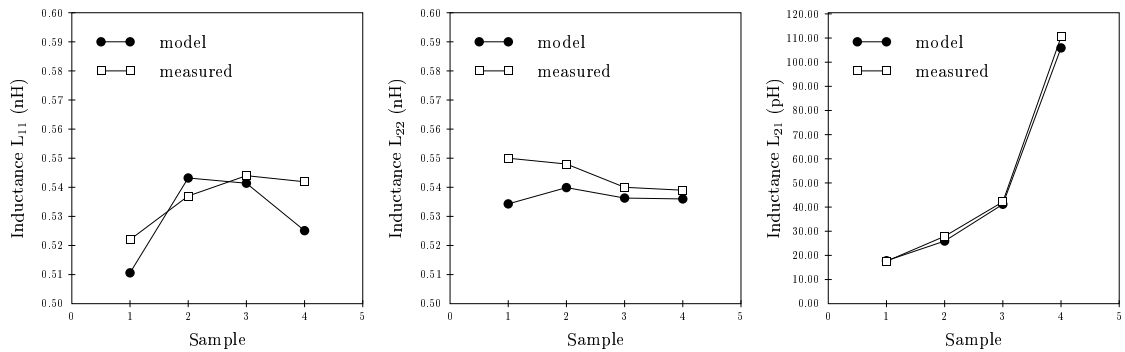


Figure 5: Self inductances L_{11} (shown on the left) and L_{22} (middle) and mutual inductance L_{21} (right) for four sets of coupled wires with a horizontal length LH_w of approximately $1000 \mu\text{m}$. The spacing between the wires S_w is 600, 500, 400 and $200 \mu\text{m}$ for samples 1-4 respectively.