Modeling and Optimization of Bond Wires as Transmission Lines and Integrated Antennas at RF/Microwave Frequencies

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Abstract

In this contribution, we present a systematic approach for optimizing the RF performance of bond wires. First of all, a comparative analysis between two of the most commonly used bond wire signal configurations, the two-conductor and coplanar configurations, is done. Our results reveal that although the partial self-inductance of the signal wires is the same in both configurations, the partial mutual inductance of the coplanar configuration is higher, resulting in a smaller loop inductance. Consequently, the return and insertion losses are smaller. By reducing the distance between the signal and return currents, we further reduced the loop inductance, and significantly optimized the coplanar configuration. For example, considering a 1 mm long bond wire with a diameter of 25 µm, we successfully kept the power lost through the coplanar configuration below 10% at 15 GHz, in comparison to the 70% power lost through the two-conductor configuration at the same frequency. However, more than 30% of the entire power is lost through the optimized coplanar configuration at 40 GHz. At such frequencies where bond wires are unsuitable to be used as transmission lines, we demonstrate that they are very efficient as antennas by designing a half-loop integrated bond wire antenna having a bandwidth of 3 GHz. For experimental verification, test samples were designed, fabricated and measured. An excellent correlation was obtained between simulation and measurement.

Keywords: Bond wire, transmission line, integrated antenna, bond wire antenna.

1. Introduction

For about three decades now, wire-bonding technology has been the most widely used chip-interconnection method [1]. Consequently, much research effort has been dedicated to study their electrical, thermal and thermo-mechanical behaviour. With regards to electrical design, the focus of previous research work has been on developing methods for quantifying the RF performance of bond wires in transmitting signals to and from integrated circuits (ICs) as well as in serving as paths for power delivery to switching ICs. In these works, bond wires are modelled and analyzed as transmission lines using a combination of numerical, analytical and experimental techniques (e.g., in [2] – [7]). The extracted models are then used to characterize the RF performance of bond wires over a wide range of frequencies. The results of most of these characterizations reveal that bond wires are not suitable for signal transmission at upper microwave frequencies, mainly as a result of their large insertion and return losses. However, up to date, techniques to minimize these losses have not been extensively discussed in published literature. The primary goal of our research is to fill this gap.

In this work, we present a systematic approach to minimize the insertion and return losses of bond wires and hence, optimize their RF performance as transmission lines. Our approach leads to a significant reduction of these losses, keeping the amount of power lost through the bond wire below 10% at frequencies up to 15 GHz. At frequencies above 30 GHz , where the parasitic effects of bond wires make them unsuitable to be used as transmission lines, we demonstrate that they are very efficient as integrated antennas, by designing a half-loop bond wire antenna having a bandwidth of 3 GHz.

The rest of this paper is organized as follows: In section two, bond wires are modeled and optimized as transmission lines and in section three, they are modelled as integrated antennas. In section four, the fabrication and measurement of test samples of bond wires as transmission lines and antennas are presented. As will be seen in this section, a very good correlation is obtained between measurement and simulation.

2. Modeling and Optimization of Bond Wires as Transmission Lines

The severe insertion and return losses caused by bond wires are mainly as a result of their large loop inductances and conductor losses. Hence, one way to reduce these losses is to minimize the parasitic inductance. Therefore, our systematic approach for optimizing bond wires as transmission lines involve two steps. 1) Choosing the right bond wire configuration for reducing the parasitic loop inductance of the signal wires. 2) Optimizing the geometrical parameters of the chosen configuration, so as to further minimize the parasitic inductance.

2.1. Choice of Bond Wire Signal Configuration

Two of the most commonly used bond wire signal arrangements are two-conductor and coplanar configurations. The two-conductor configuration consists of a signal and reference wire, while the coplanar configuration is made up of a signal wire and two reference wires. In Figure 1, the 3D and side views of both configurations are shown. Each bond wire has a diameter of 25 µm, length of 1mm and is bonded to a square pad (35 µm * 35 µm). Each pad is connected to a microstrip transmission line, having the same width as the pad. The chip and interposers on which the wires are bonded are 200 µm and 300 µm thick, respectively. Both have a metallization thickness of 17 µm.

In order to choose the optimal configuration for signal transfer, we modelled and compared both configurations from 500 MHz to 20 GHz using Ansoft HFSS (High Frequency Structure Simulator). HFSS applies the finite element method to solve Maxwell’s equations in the frequency domain. For the electromagnetic field simulations, wave ports were used for the excitation and PML (perfect matching layers) were assigned as the boundary conditions. After the field simulations, the microstrip lines are de-embedded such that only the square pads and the bond wires are left. A comparison of the insertion and return losses obtained for both configurations is shown in Figure 2. All the curves are renormalized to a port impedance of 50 Ohms. As seen from these curves, the RF performance of the coplanar configuration is better than that of the two-conductor configuration. This is mainly because although the partial self-inductance of the signal wires in both configurations is the same, the partial mutual inductance in the coplanar configuration is much higher than that of the two-conductor configuration. Consequently, the parasitic loop inductance of the signal wire in the coplanar configuration is smaller. This smaller loop inductance results in a smaller discontinuity caused by the bond wire. Consequently, the impedance mismatch, return and insertion losses are smaller.

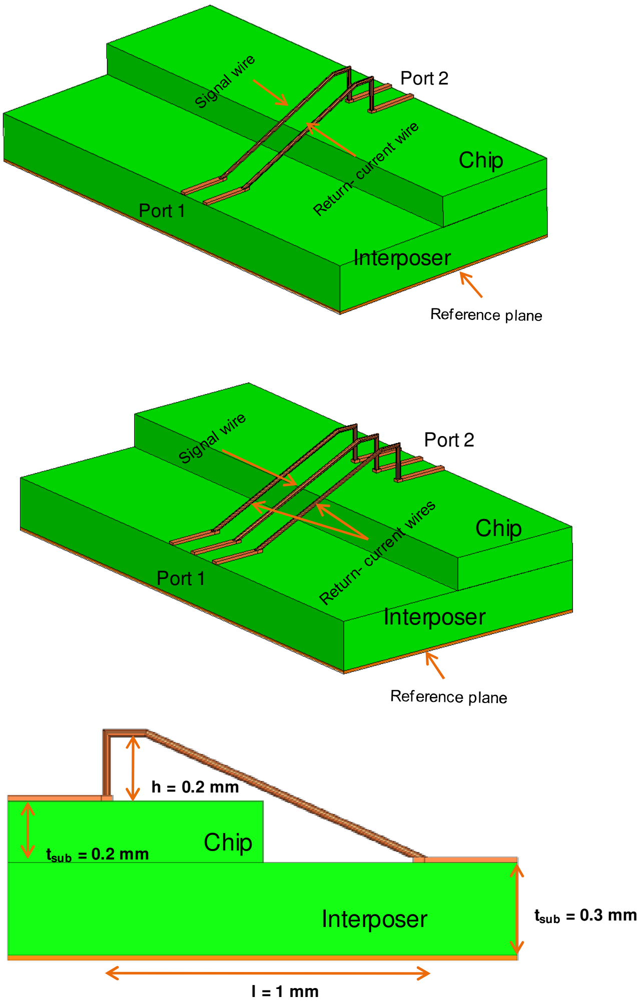

Figure 1: 3D and side views of bond wire models used for simulation: Two-conductor configuration (top); coplanar configuration (middle): side view (bottom). t_{sub} represents the interposer and chip thickness.

To better quantify the difference in RF performance between both configurations, we depict in Table 1 the power lost at some important frequencies used for wireless and high-speed data applications. The frequencies chosen are for GSM 900/1800, 2.4/5 GHz WLAN (Wireless Local Area Network), 10 GHz UWB (Ultra Wide Band) as well as 20 GHz for high-speed data applications. As can be seen from this table, despite the fact that coplanar configuration is better, it cannot be used for applications above 10 GHz (without prior optimization) because more than 20% of the power to be transmitted along the bond wire is lost. At 20 GHz approximately half of the power is lost. Our goal is to keep the amount of power lost through the bond wire below 10% at 15 GHz.

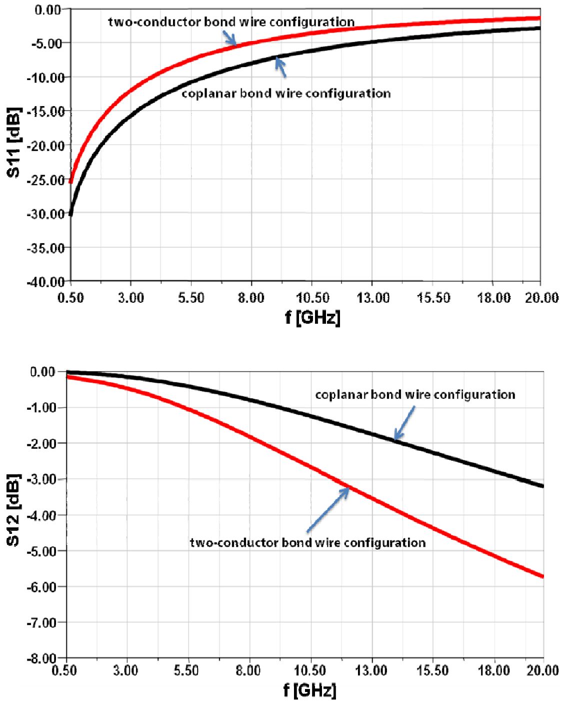

Figure 2: Comparison of return and insertion losses of two-conductor and coplanar bond wire configurations.

Frequency [GHz]	0.9	1.8	2.4	5	10	20
Power loss two–conductor configuration [%]	4.5	6.6	8.4	19.3	43.9	73.3
Power loss Coplanar configuration [%]	0.67	1.6	2.4	7.8	23.3	52.1

Table 1: Approximate values of power lost through two-conductor and coplanar bond wire configurations.

2.2. Optimization of Chosen Configuration

To minimize the loop inductance of bond wires, the total magnetic flux must be reduced. This can be achieved by reducing the distance of separation between the signal and return–current paths. For the chosen coplanar configuration, this implies that the pitch as well as the loop height must be reduced. Considering fabrication constrains, we achieved an optimal loop height and pitch of 200 µm and 50 µm, respectively. As can be seen in Figure 3 and Figure 4, by reducing the pitch and the loop height, a considerable reduction in insertion loss is obtained. For example, considering a 1 mm long bond wire with a diameter of 25 µm, we successfully kept the power loss through the coplanar configuration below 10% at 15 GHz, in comparison to the 70% power lost through the two-conductor configuration at the same frequency. The comparison in insertion loss between the optimized coplanar configuration and the standard two-conductor bond wire configuration is shown in figure 5.

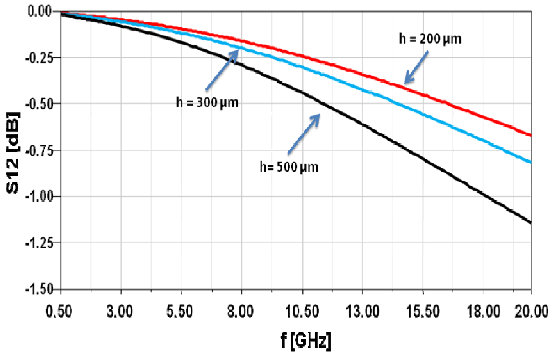

Figure 3: Optimizing RF performance of bond wires by reducing the loop height (Pitch=50 µm). h= loop height.

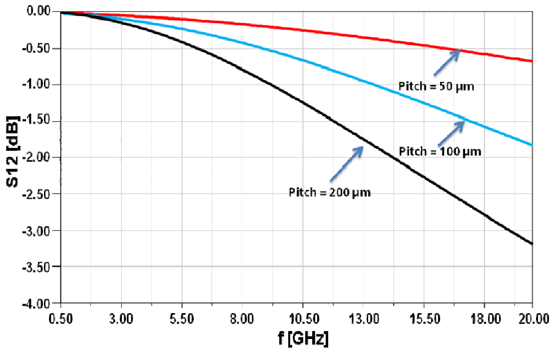

Figure 4: Optimizing RF performance of bond wires by reducing the pitch (Loop height = 200 µm).

However, as can be seen in this figure, the insertion loss of the optimized configuration deteriorates with frequency. For example at 40 GHz, more than 30% of the entire power is lost. As a result of such huge losses, the optimized configuration becomes unsuitable to be used as transmission line. In the next section, we demonstrate that at such frequencies where the bond wires are unsuitable for signal transmission, they are very efficient as antennas.

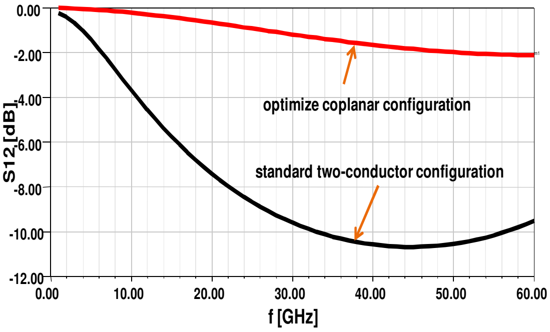

Figure 5: Comparison of insertion loss between two-conductor and optimized coplanar bond wire configuration.

3. Bond Wires as Integrated Antennas

To demonstrate the efficiency of bond wires as antennas at millimeter-wave frequencies, we designed a vertical half-loop bond wire antenna above a ground plane, fed by a 3mm long coplanar transmission line. In figure 6, the 3D model of the antenna is shown. The antenna was designed to operate at approximately 39 GHz. For this purpose, a bond wire of length 3mm and loop height of 250 µm was used.

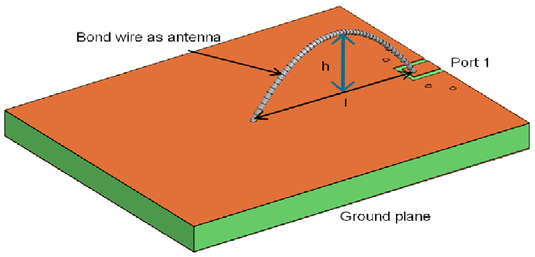

Figure 6: Bond wire as antenna: Loop height (h) = 250 µm; wire length (l) = 3 mm.

In figure 7, the insertion loss of the bond wire antenna is shown. As seen from this figure, the integrated bond-wire antenna resonates very well at a frequency of approximately 39.2 GHz, with a good return loss of approximately 34 dB. Using a loop height of 250 µm, a large bandwidth of 3 GHz (@ -10 dB) was achieved. This makes bond wire antennas particularly suitable for millimetre-wave applications, where more bandwidth is required for high-speed data transmission.

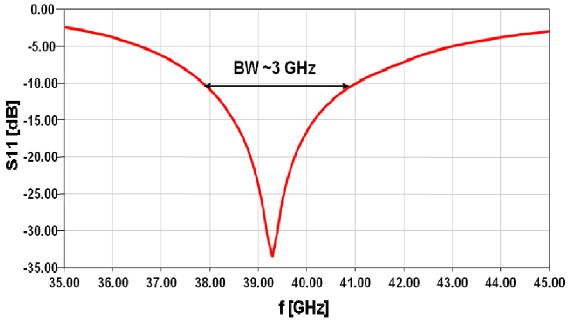

Figure 7: Return loss of bond wire antenna.

4. Fabrication and Measurement of Test Samples for Experimental Verfication

For experimental verification, test boards were designed, fabricated and then wire-bonded. The wires were bonded using a Delvotec 5630 Al-wedge/wedge wire bonder. An AlSi1 wire with 25 µm diameter and a standard bonding tool (flat bonding foot, foot length 50 µm, non fine-pitch) was used. Bonding on the Cu/Ni/Flash-Au metallization of the PCBs was performed at room temperature. The bonding process optimization was focused on loop shape optimization. By using reverse movement and high loop height settings the intended loop shape could be bonded.

After fabrication, the bond wires were measured using a vector network analyzer. The measurement setup consists of a vector network analyzer (VNA) - HP 8510 C, a probe station, and a pair of coplanar probes (pitch = 300 µm) connected to the VNA using coaxial cables. Since the measurement equipment introduces many errors, it was calibrated prior to the measurement of the test structures. Due to its high degree of accuracy, the line-reflect-reflect-match (LRRM) method was used in this study together with an impedance standard substrate (ISS) from Cascade Microtech. After the calibration, the measurements were performed from 500 MHz to 45 GHz. The measurement results were then compared with the simulation results.

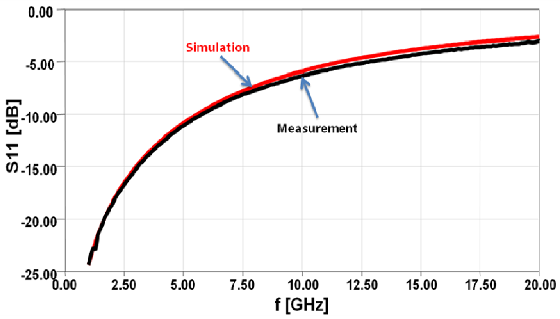

Figure 8: Comparison between measurement and simulation results for bond wires as transmission lines (return loss considered).

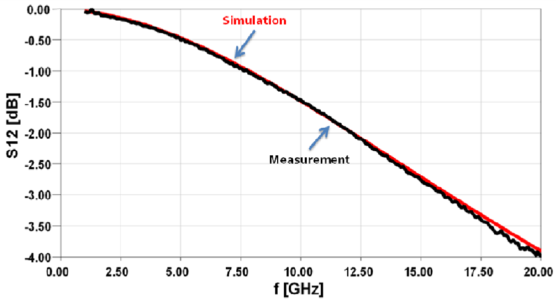

Figure 9: Comparison between measurement and simulation results for bond wires as transmission lines (insertion loss considered).

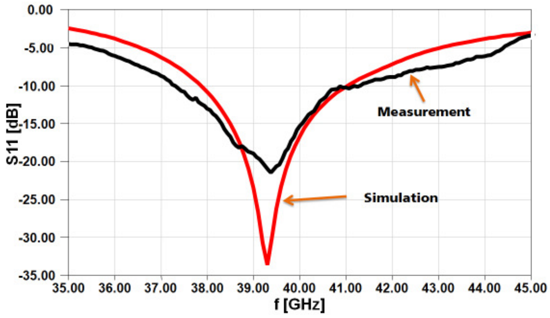

Figure 10: Comparison between measurement and simulation results for bond wires as an integrated antenna.

As can be seen in figures 8, 9 and 10, very good correlation was obtained between measurement and simulation for both cases – bond wire as transmission line and as antenna. The coplanar bond wire configuration used for the RF measurements had the following dimensions: Length of bond wire= 1 mm, loop height= 200 µm and pitch of 350 µm. During the design, this large pitch was considered, taking into account the available coplanar probes to be used for the RF measurements.

5. Summary

We modeled, design, fabricated, measured and optimized bond wires as transmission lines and antennas. Since the wire-bonding technology is a well established chip-interconnection method, we recommend that it should be used as antennas at frequencies where the insertion and return losses prevent their application as transmission lines.

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