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Analysis of Bond Wires and Proposal for Compensation Circuits in 73 GHz Applications

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***Abstract*— This work investigates the problems associated with bond wire interconnection in millimeter wave applications. The deteriorating effect of bond wire caused by the inductance and other parasitic parameters in the bond wire is analyzed against frequency. To improve the insertion loss and matching associated with bond wire, an impedance compensation circuit is designed at 73 GHz consisting of a radial stub and microstrip line. Furthermore, simulations shows that the degradation in transmission loss performance and matching can be minimized by reducing the overall length of bond wire and increasing the diameter. The proposed solution is verified by the measurements of a 25 um diameter bond wire with and without compensation structure. The measured insertion loss is reduced to -3.5 dB, compared to the -6dB insertion loss in bond wire interconnect without compensation. Moreover, the input and output return loss are better than -10 dB at 73 GHz. Significant improvements in terms of transmission performance and impedance matching are observed, compared with an unmatched bond wire.**

Keywords— bond wire, compensation circuit, impedance matching, inductance, insertion loss, millimeter wave, wire bonding.

I. Introduction

With the recent developments in communication technology, the need for miniaturization of microwave circuits has spurred the development of 3-D packaging techniques, including chip and package assembling, which are crucial for achieving compact designs [1,2]. Multichip assembly technology is particularly effective in this regard. Within microwave multichip modules (MCMs), bond wires remain essential for interconnection due to their easy fabrication process and cost effectiveness. However, as the signal frequency increases, bond wires can exhibit high insertion loss and degrade transmission. This is because of wire inductance and parasitic parameters, leading to signal integrity issues. Therefore, it is crucial to examine, and improve the characteristics of bond wires in milllimeter wave circuits.

There are only a few models in the literature that characterize bond wires. One approach is a behavioural model described in [3], which produces an input impedance derivation from the measurements of a network analyzer. Similarly, Xue et al. [4] developed a method of modelling bond wires of arbitrary shapes using lumped element models. Other techniques, as detailed in [5]–[7], involve direct calculations of S- and Y-parameters using causal equations or the finite-difference time domain (FDTD) method. These advanced models account for generalized cases, including irregularly shaped wires.

There are numerous methods to address the impedance mismatch of bond wires. Generally, bond wires act as inductive interconnects, with impedance that increases with frequency. To minimize their parasitic effects in a circuit, various methods are used to reduce the mismatch caused by the interconnect between the chip and the circuit. By using a broadband line with lower impedance or reducing the space between the bond pads, thereby shortening the bond wire, the inductive effects can be decreased [8,9]. However, these techniques increase costs and production challenges. Enhancements in insertion loss and matching have been reported in [10,11], by employing a through capacitive compensation structures. Generally, to enhance manufacturability, it is preferable to increase the bond wire length and size. Nevertheless, increased operating frequency and wire length lead to higher insertion loss. To counteract this, circuit compensation techniques have been proposed. One approach involves a bond-wire circuit with a five-stage low-pass filter as an interconnect prototype, which can significantly expand bandwidth and accommodate longer bond wires, though at a higher cost and with greater implementation difficulty [12]. Another method, the T network, compensates for the series inductance of bond wires but requires a large area for the inductors and capacitors on the package [13].

In this study, we investigate the problems associated with bond wires for interconnection in millimeter wave applications and also proposes compensation circuits for improving the matching. This paper is organized as follows: Section II discusses the simulation of the bond wire and the parametric analysis of the bond wire. Section III presents the design of the matching compensation structure at 73GHz. Sections IV discusses the measurements of bond wire with and without compensation structure. Finally, Section V presents the conclusions.

II. Bond Wire Simulation

In this work, a single bond wire made of gold with a diameter of 25 µm is initially used. Bond wire pads have a length of 100 µm and width of 450 µm, with characteristic impedance of 50 Ω to satisfy the impedance matching requirements. The spacing between the bond-wire pads is set as 320 µm and a 40 µm offset is used in both ends of the bond wire to the edge of the pad. Thus, the overall length of the bond wire is estimated as 480 µm. A low loss Rogers substrate RO4003C with a thickness of 200 µm is selected for this study. A copper ground plane is also placed on the other side

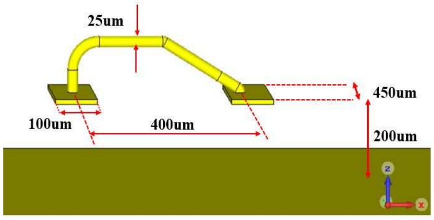

Fig. 1 Simulation model of the bond wire.

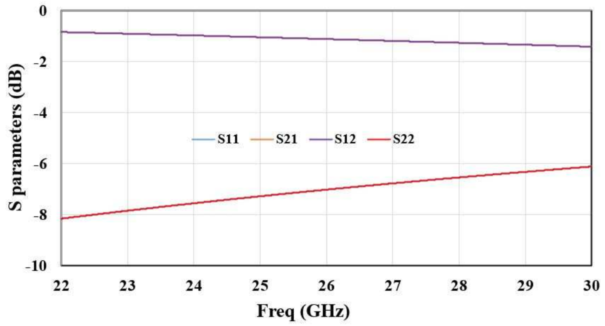

Fig. 2. Simulation S parameter results of the bond-wire interconnection at low millimeter frequency range 22 to 30 GHz (S11 & S22 identical, S21 & S12 identical).

of the substrate. Fig. 1 shows the simulation model of the bond wire.

Initially, the bond wire is simulated for 22 to 30 GHz for analysing the performance in low millimetre applications as shown in Fig. 2. It can be observed that the transmission characteristics of the bond wire is degrading with frequency. This is mainly due to the inductive effect of bond wire. Even though the insertion loss is increasing with frequency, it is less than 2 dB at 30 GHz. Similarly, the reflection coefficient is in the range of -8 to -6 dB. Thus, the impact of bond wire in the low millimeter-wave region is present but perhaps not severe.

With the recent developments of RF chips for beyond 60 GHz applications, it is necessary to investigate the bond wires, which can be used as chip to PCB interconnection for off-chip antennas. To have a better understanding of the deteriorating effect of the bond wire in our required frequency range, it is simulated for 70 to 76 GHz and the results are shown in Fig. 3. More than a 3 dB loss can be observed in the transmission performance. The insertion loss S21 is already less than -4 dB, and the reflection coefficient is around -2 dB. Therefore, it is necessary to consider the parasitic effects of the bond wire and to perform the required compensation to achieve a good impedance matching and better transmission performance.

For investigating the effects of the parameters of a bond wire, the length and diameter is varied, and RF performance analysed. The overall length of the bond wire is varied from 480 µm to 1 mm without changing the location of bond wire pads. Fig. 4 shows the S parameter results of the bond wire interconnection with the change in length. The insertion loss

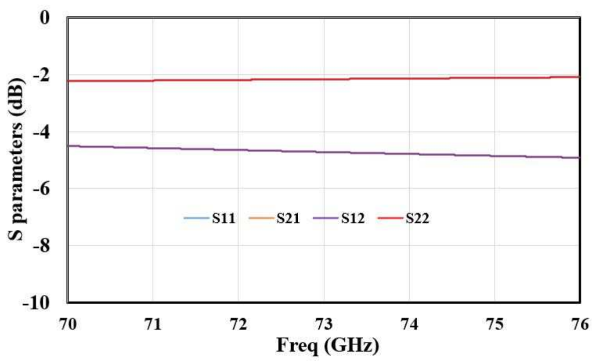

Fig. 3. Simulation S parameter results of the bond-wire interconnection at low millimeter frequency range 70 to 76 GHz.

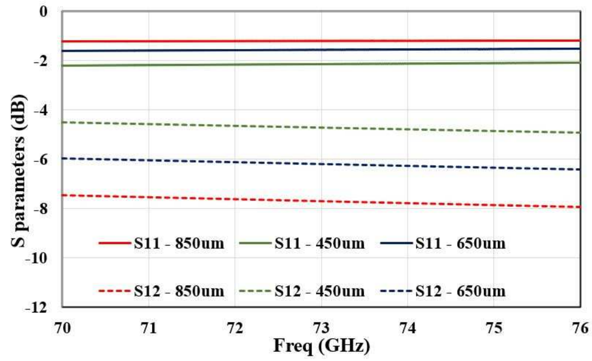

Fig. 4. S parameter results of the bond-wire interconnection with the change in length.

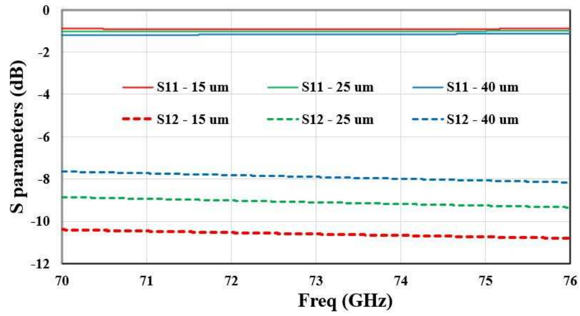

Fig. 5. S parameter results of the bond-wire interconnection with the change in diameter.

is increasing from -4 dB at 70 GHz for a 450 µm bond wire to -6 dB while the overall length of the bond wire increased by 200 µm. S11 also degrades from -2 dB. Similarly, a 850 µm bond wire has an insertion loss of -8 dB and reflection coefficient is around -1 dB. Thus, it is necessary to reduce the overall length of the bond wire to reduce the effect of self-inductance and thereby improving the transmission performance.

Varying the diameter of the bond wire significantly affects the insertion loss as shown in Fig. 5. Fig. 5 shows the S parameter results of the bond-wire interconnection with the change in diameter from 15 µm to 40 µm keeping the overall length constant at 950 µm. It can be observed that the insertion loss can be improved by increasing the diameter of the bond wire. A small diameter of 15 µm results in -10 dB insertion loss, whereas 40 µm has only -7.5dB loss. However, the diameter is limited to 25 µm in this work, is due to the specification of the wire bonder.

III. Compensation Circuit

To cancel out the effect of the series inductance due to the bond wire interconnection, a capacitive radial stub is utilised along with a thin impedance transformation microstrip line. The angle and radial length of the radial stub is initially estimated from calculations in ADS and then optimised by

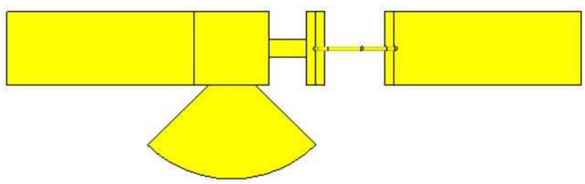

Fig. 6. Matching compensation circuit layout with bond wire.

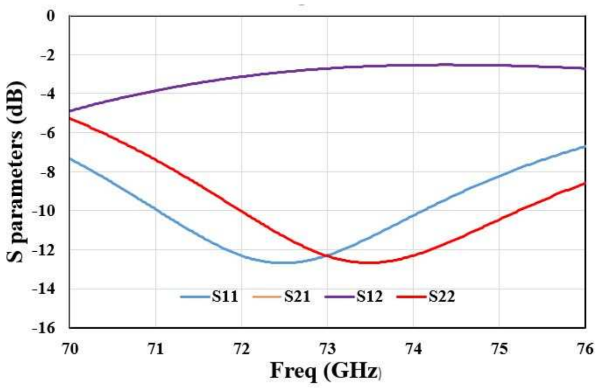

Fig. 7. Simulated S parameters of the compensation circuit.

CST for fine tuning. Fig. 6 shows the layout of the matching compensation circuit with single bond wire. The microstrip line has a length of 200 µm and width of 100 µm. The radial stub has a radial length of 460 µm.

Fig. 7 shows the simulated S parameters of the compensation circuit with single bond wire of length 480 µm and diameter 25 µm. It can be seen that the compensation structure makes the transmission loss S21 parameter of the bonding wire reduces to a value of -2.7 dB from -4.7 dB at 73 GHz. Moreover, the return-loss S11 parameter is less than −12 dB compared to -2 dB. Return loss bandwidth is also more than 2 GHz.

IV. Measurement Results

To validate the study, initially a PCB board is fabricated with and without the compensation network. Fig. 8 shows the probe station for S parameter measurement, performed at UKRI millimeter wave lab at TUoS [14]. With a frequency range up to 76 GHz, measurements are taken by a Keysight PNA N5245B, WR15+ VDI extenders and 100um pitch RF probes, calibrated with a two-port thru-reflect-line (TRL) calibration process on the same substrate to remove the effect of the fixture. Fig. 9 shows the single bond wire interconnects manufactured by a semiautomatic wire bonding machine in our lab. A 1 mm long microstrip line and a tapering line are used on both sides of the gold bond wire to connect it to the GSG pads with 100 um pitch. Fig. 10 shows the measured results of a single bond wire. It can be observed that the insertion loss S21 is around -6 dB compared to simulated

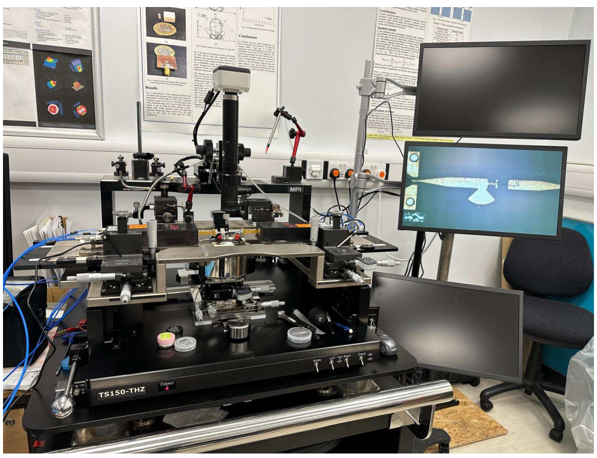

Fig. 8. Probe station for S parameter measurement.

Fig. 9. Fabricated single bond wire.

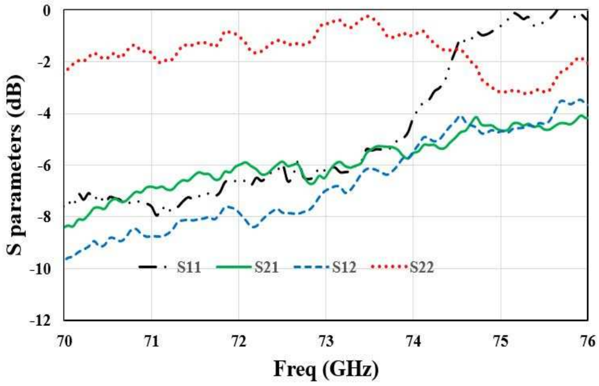

Fig. 10. Measured S parameters of the single bond wire.

value of -4.5 dB for an overall length of 480 µm. This can be due to the increased length of bond wire, since the length cannot be sufficiently controlled in a manual wire bonding machine.

Fig. 11 shows the fabricated compensation circuit with the single bond wire. Measured S parameters of the bond wire interconnect with compensation circuit is shown in Fig. 12. It can be observed that the insertion loss is reduced to -3.5 dB compared to the -6 dB insertion loss in the bond wire interconnect without compensation. Moreover, the return loss curves S11 and S22 are also better than -10 dB at 73 GHz. Best performance of the compensation circuit can be seen at 76 GHz. At 76 GHz, insertion loss is around -2.5 dB - very similar to the simulated insertion loss. Reflection coefficient curves S11 and S22 are better than -15 dB at 76 GHz. This shift in centre frequency may be due to the PCB fabrication tolerances and the suspected increased length of the bond wire. A remarkable improvement in terms of insertion loss and impedance matching can be observed with the addition of the proposed compensation circuit.

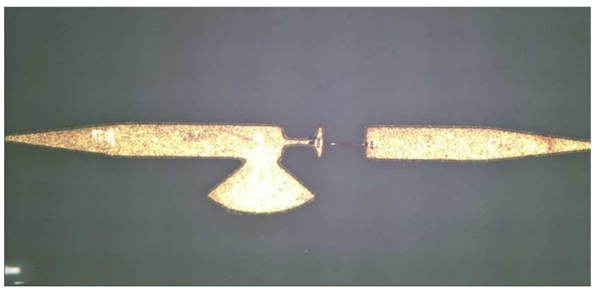

Fig. 11. Fabricated single bond wire with impedance compensation.

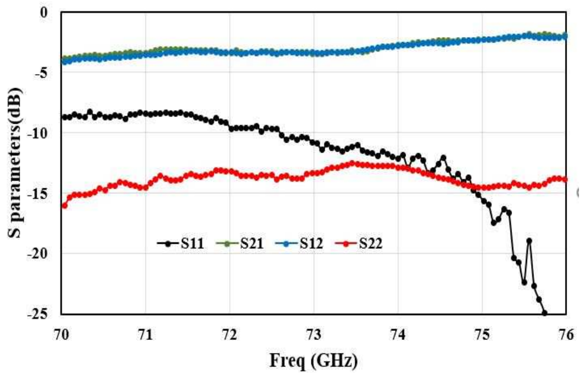

Fig. 12. Measured S parameters of the bond wire interconnect with compensation circuit.

V. CONCLUSIONS

This work addressed the challenges associated with bond wire interconnections in millimeter-wave applications, specifically the detrimental effects caused by inductance and other parasitic parameters. Simulations demonstrated that reducing the overall length and increasing the diameter of bond wires can minimize degradation in transmission loss and matching. By analyzing these effects across different frequencies, we designed an impedance compensation circuit at 73GHz, incorporating a radial stub and microstrip line to improve insertion loss and matching. Verification through measurements showed that the proposed compensation structure reduced the insertion loss to -3.5 dB, compared to -6 dB without compensation. Additionally, the return loss curves (S11 and S22) were better than -10 dB at 73 GHz (and -15 dB at 76 GHz). These results demonstrate considerable enhancements in transmission performance and impedance matching can be obtained by adopting the compensation circuit design for high millimeter wave applications.

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