RF Modeling of Ball Grid Array Packages Using a Coupled Transmission Line Model

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***Abstract* — A novel method for radio-frequency (RF) modeling of ball grid array (BGA) packages is presented. A new analytical method is developed to extract the inductance characteristics of the package bond wires. With the extracted bond wire data, a cascaded multi-section coupled transmission line model is setup to describe the physical trace structures of the BGA packages. The multi-section π model representing the coupled transmission line effect of the signal traces is used for the RF modeling of the BGA packages. The BGA packages with open-path, short-path, through-path, and through-ground test configurations are studied. The simulated S parameter results exhibit great agreement with the measured ones for the BGA packages.**

I. INTRODUCTION

Recently, the integration of multi-function circuits in a single integrated system is an emerging technology for radio-frequency (RF), digital, and mixed-signal applications. The trend of the complex integrated circuits with increasing input/output (I/O) pins pushes the need for the packages with high pin counts. The ball grid array (BGA) packages [1]-[2] can provide high pin counts for high integration of circuits and systems. In addition, the BGA packages have the advantages of easy surface mounting and low production costs.

The BGA packages have a great number of traces with different length and spacing. The electrical characteristics of the IC in a BGA package are strongly affected by the package. An accurate RF model of a package is essential for circuit designers to design a successful IC [3]-[5]. However, the RF modeling of the BGA packages is a critical challenge because of the parasitic and coupling effects of the complex traces of the packages [4]-[8].

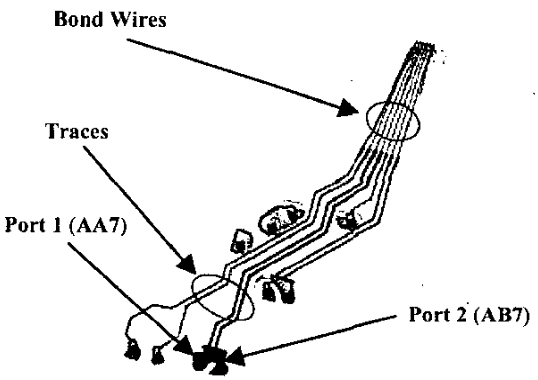

Fig. 1. A part of trace layout of BGA package for RF modeling.

In this paper, we present a state-of-the-art RF modeling method for the BGA packages. The method is based on the RF measurement of the BGA packages with open-path, short-path, through-path, and through-ground configurations using a vector network analyzer. A cascaded multi-section coupled transmission line model and a multi-section π model are used for the modeling of the packages. The modeling results show that the proposed method is able to provide excellent agreement between the simulated and measured S parameters over a frequency range up to 6 GHz.

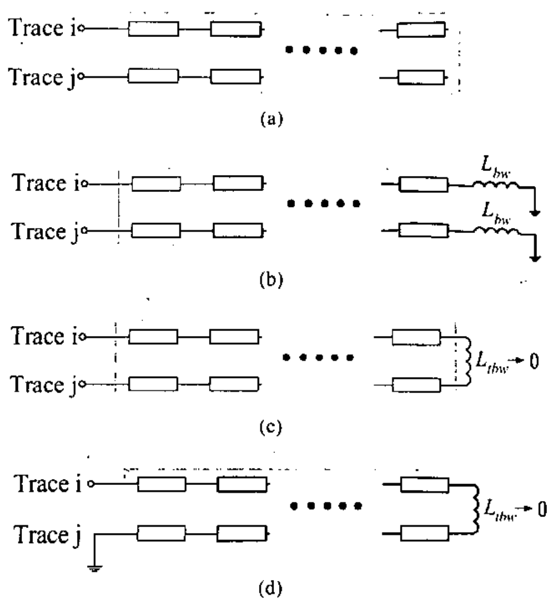

Fig. 2. RF modeling schemes associated with test configurations. (a) Open-path. (b) Short-path. (c) Through-path. (d) Through-ground.

II. Package Structure

The measurement samples for the RF modeling are four-layer plastic BGA (PBGA) packages with an array of 448 balls. The body size of the package is 23 × 23 mm^2. The ball pitch is 1.0 mm. The signal traces of the packages are individually connected to the balls through different vias. The test traces for the RF measurement are AA7 and AB7. Fig. 1 shows a part of the trace layout of the BGA package for the RF modeling.

III. Method of Modeling

For the RF modeling of the BGA packages, there are four test configurations: open-path, short-path, through-path, and through-ground. The RF modeling schemes associated with the test configurations are shown in Fig. 2. The coupled traces of the BGA packages are modeled by the cascaded multi-section coupled transmission lines. The RF measurement is conducted using the vector network analyzer and a pair of signal/ground (S/G) microwave probes. In the RF measurement, the traces other than the test traces (AA7 and AB7) are grounded through gold bond wires. For the open-path configuration, the test traces under measurement are open-ended while the remaining traces are shorted to the ground. In the short-path configuration, all the traces including the test traces under measurement are grounded through bond wires, as shown in Fig. 1. Both the test traces under measurement are connected together through bond wires for the through-path configuration. The through-ground configuration is similar to the through-path configuration but not the same. Not only both the test traces under measurement are connected together through bond wires but also one of the test traces has a grounded ball.

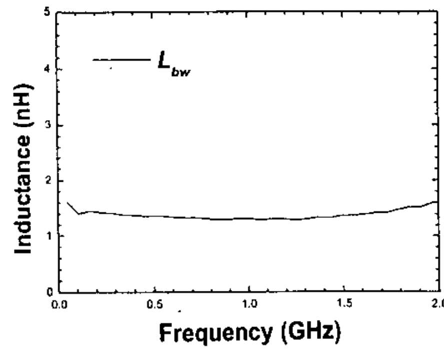

Fig. 3. Extracted inductance characteristics of bond wires for short-path test configuration.

The bond wires in the short-path test configuration is extremely longer than the bond wires in the through-path and through-ground test configurations. The inductance of the bond wire (L_{bw}) for the short-path test configuration must be taken into account while the inductance of the through bond wire (L_{tbw}) in the through-path and through-ground test configurations is ignored. On the basis of the RF measurement of the BGA test samples, the L_{bw} can be derived analytically at low frequencies. We have

$$L_{bw} = \frac{Z_o}{4\pi f} \mathrm{Im}\left[\frac{1+S_{sp11}}{1-S_{sp11}} + \frac{1+S_{sp22}}{1-S_{sp22}} - \frac{4S_{sp12}}{(1-S_{sp11})(1-S_{sp22})} - \frac{1+S_{tg11}}{1-S_{tg11}}\right] \quad (1)$$

where Z_o is the characteristic impedance (50 Ω), f is the signal frequency, S_{sp} is the measured S parameters of the package in the short-path configuration, and S_{tg} is the

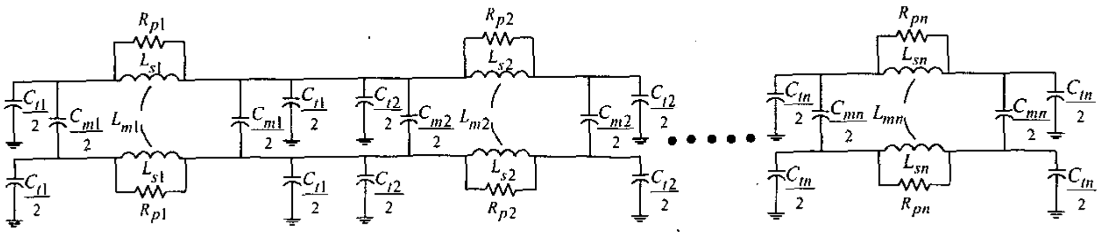

Fig. 4. Multi-section π model for BGA package.

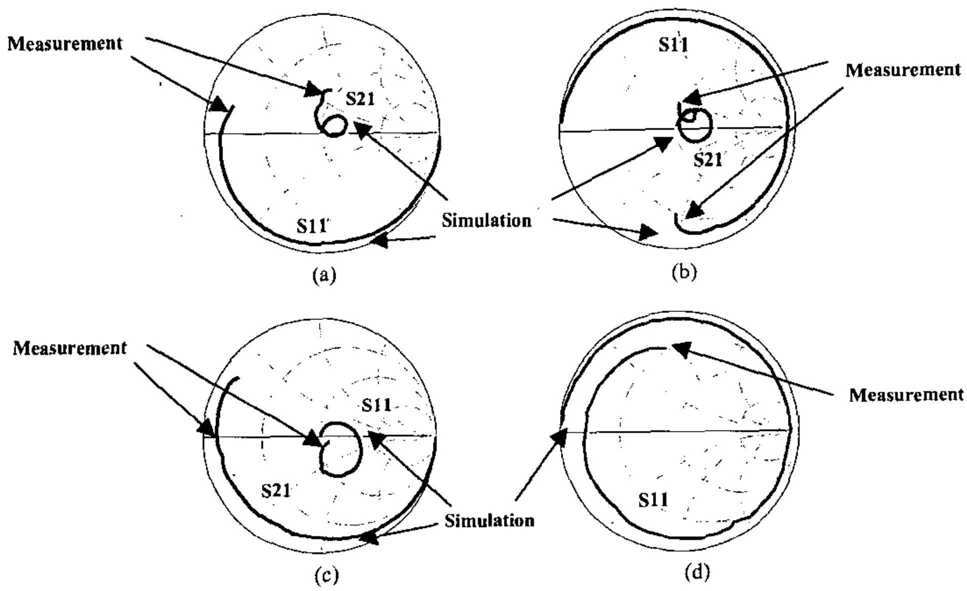

Fig. 5. Comparison of simulated and measured S parameters. (a) Open-path. (b) Short-path. (c) Through-path. (d) Through-ground.

measured S parameters of the package in the through-ground configuration. Fig. 3 shows the extracted L_{bw}. The value of the L_{bw} at 1 GHz is 1.31 nH.

The cascaded multi-section coupled transmission lines representing the coupled traces of the BGA packages are characterized by the even-mode and odd-mode characteristic impedances as well as the even-mode and odd-mode propagation velocities. The associated resistances with the coupled transmission lines are considered to include the frequency-dependent losses from skin effects. In conjunction with the extracted L_{bw}, the even-mode and odd-mode propagation parameters and the associated resistances of the multi-section coupled transmission lines are optimized for the BGA packages with open-path, short-path, through-path, and through-ground test configurations. In this paper, a three-section coupled transmission line model is used to perform the optimization process.

The extracted parameters of the multi-section coupled transmission lines are then transformed to a multi-section

π model according to the theory of the coupled transmission lines [9]. Fig. 4 shows the multi-section π model transformed from the multi-section coupled transmission line model. In the i-th section of the multi-section π model, C_{ti} is the total capacitance, C_{mi} is the mutual capacitance, L_{si} is the self inductance, L_{mi} is the mutual inductance, and R_{pi} is the parallel resistance for individual-section coupled transmission line. The elements of the multi-section π model are optimized with respect to the measured S parameters of the packages in the open-path, short-path, through-path, and through-ground test configurations. Fig. 5 shows the simulated and measured S parameters of the BGA packages. The simulated S parameters based on the multi-section π model agree well with the measured S parameters from 0.02 to 6 GHz.

IV CONCLUSION

A novel RF modeling method has been developed for the BGA packages. The RF modeling of the BGA packages is based on a new analytical approach for the extraction of the inductance characteristics of the package bond wires. The modeling method involves the even-mode and odd-mode propagation effects in the coupled transmission lines of the BGA packages. Excellent agreement between the simulation and measurement results has been demonstrated. The efficient method developed provides an accurate RF modeling technique for the variety of the BGA packages.

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