Circuit Modeling of Multi-Layer Ceramic Capacitors Using S-Parameter Measurements

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Abstract— MLCC (Multi Layer Ceramic Capacitor) is characterized in the frequency range of 50MHz to 20GHz by using s-parameters. A test fixture that mounts an MLCC is designed with printed circuit board (PCB). Then the MLCC is characterized by using VNA and Impedance Analyzer. The circuit model parameters of the MLCC are extracted and its validity is verified.

Keywords— Multi Layer Ceramic Capacitor (MLCC), Equivalent series resistance (ESR), Equivalent series inductance (ESL), Transmission lines, De-embedding.

I. INTRODUCTION

As the operation frequencies of integrated circuits or systems drastically increase, the power and ground integrity of the circuits become one of crucial circuit design issues. Today’s integrated circuit or system requires their variations, in general, be controlled within 5% to 10% of given voltage swing [1], [2]. The power and ground bouncing are due to the parasitic inductances of the lines [3]-[5]. Thus, in order to compensate for the inductance effects, very large capacitances, so called decoupling capacitances, are employed in many practical circuit or system design.

Up to date, a few techniques for the characterizations of MLCCs have been developed [6]-[10]. However, these techniques are neither rigorous nor accurate since their characterization algorithms are, in many parts, resorted to data fitting. Thus, a more accurate characterization technique is highly required.

In this research, a new accurate high-frequency MLCC characterization method is presented. Next, circuit model parameters are directly extracted from the measured s-parameters. Then the accuracy of the proposed circuit model is verified.

II. EXPERIMENTAL CHARACTERIZATIONS

A test fixture for an MLCC characterization is designed as shown in Fig. 1. One terminal of MLCC (i.e., DUT) is mounted on a signal line pad and the other terminal of MLCC is mounted on a ground line pad. Since the DUT cannot be directly contacted with the proving pads, a signal line and ground lines (i.e., so called “access lines”) are connected with measurement proving-pads. Note, although the access lines and DUT mounting-pads are inevitable for on-wafer probing, they have a significant effect on the measurement accuracy. Thus, the parasitic effect has to be de-embedded.

A. DUT Characterizations

The test fixture is a 2-port microwave network. Thus, its measurement network configuration for 2-port s-parameter measurements can be represented as shown in Fig. 2. For the s-parameter measurement, VNA (vector network analyzer) is calibrated up to the probe tips by using SOLT (short, open, load, thru) calibration method. Since the measurement reference impedance is 50 ohm, the characteristic impedance of the access lines are considered the transmission lines was designed to be 50 ohm. Then, since the s-parameter measurement reference planes are the proving pads, the measurement reference planes are shifted from the proving pads to the location right before the DUT.
If the characteristic impedance of the access lines is matched with the measurement reference impedance, the DUT can be represented with the 2-port network parameters \([11]\),

\[
\begin{bmatrix}
S_{\text{Measure}}
\end{bmatrix}_T = \begin{bmatrix}
e^{j\theta} & 0 \\
0 & e^{j\theta}
\end{bmatrix} \begin{bmatrix}
S_{\text{DUT}}
\end{bmatrix}_T \begin{bmatrix}
e^{-j\theta} & 0 \\
0 & e^{-j\theta}
\end{bmatrix},
\]

(1)

where the subscript ‘T’ indicates T-parameter. Thus, if the propagation constant of the access line is determined, the DUT s-parameter, \([S_{\text{DUT}}]\), can be determined as below

\[
\begin{bmatrix}
S_{\text{DUT}}
\end{bmatrix}_T = \begin{bmatrix}
e^{-j\theta} & 0 \\
0 & e^{-j\theta}
\end{bmatrix}^{-1} \begin{bmatrix}
S_{\text{Measure}}
\end{bmatrix}_T \begin{bmatrix}
e^{j\theta} & 0 \\
0 & e^{j\theta}
\end{bmatrix}^{-1}.
\]

(2)

Once \([S_{\text{DUT}}]\) is determined, the high-frequency circuit model parameters of MLCC can be determined. That is, since an MLCC has parasitic resistance and inductance, it can be modeled as an equivalent circuit as shown in Fig. 3.

Converting the extracted DUT s-parameters, \([S_{\text{DUT}}]\), into ABCD parameters, the impedance of the DUT can be determined \([11]\),

\[
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix}_{\text{DUT}} = \begin{bmatrix}
1 & 0 \\
0 & 1
\end{bmatrix} \begin{bmatrix}
1 & 0 \\
0 & \frac{1}{Z_{\text{DUT}}}
\end{bmatrix},
\]

(3)

Then the impedance of the DUT (i.e., \([Z_{\text{DUT}}]\)) can be represented with the circuit model parameters as below

\[
Z_{\text{DUT}} = R + j(\omega L - \frac{1}{\omega C}).
\]

(4)

Note, since the dielectric constant of an MLCC does not vary with the frequency, the capacitance can be considered a constant within the measurement frequency band. Thus, the capacitance of (4) can be readily measured by using impedance analyzer at a low frequency in which the parasitic inductance can be neglected. For the MLCCs that have the nominal capacitance values of 100nF and 10nF, measured capacitances are 96.2nF and 10.5nF, respectively.

### B. Transmission Line Characterizations

In order to shift the measurement reference plane, access line has to be characterized. Since the access lines are considered a transmission line, its propagation constant and characteristic impedance have to be determined. For the sake of the transmission line characterization, the various lengths of transmission lines (5mm, 10mm, and 20mm long lines) are designed on the same test module. Then s-parameters are measured by using vector network analyzer (VNA).

The s-parameters of the transmission line can be represented as

\[
\begin{bmatrix}
S_{11} & S_{12} \\
S_{21} & S_{22}
\end{bmatrix} = \frac{1}{D_o} \begin{bmatrix}
(Z^2 - Z_o^2) \sinh \gamma l & \frac{2Z_o}{2Z_o - (Z^2 - Z_o^2)} \sinh \gamma l \\
\frac{2Z_o}{2Z_o - (Z^2 - Z_o^2)} \sinh \gamma l & (Z^2 - Z_o^2) \sinh \gamma l
\end{bmatrix},
\]

(5)

where \(D_o = 2Z_o \cosh \gamma l + (Z^2 + Z_o^2) \sinh \gamma l\). Thus, solving the equations, the propagation constant and characteristic impedance can be determined \([12], [13]\),

\[
e^{j\theta} = \frac{1 - S_{12}^2 + S_{22}^2}{2S_{21}} + \frac{(S_{11}^2 - S_{12}^2 + 1)^2 - (2S_{12})^2}{(2S_{21})^2}^{-1},
\]

(6)

\[
Z^2 = Z_o^2 \frac{(1 + S_{11})^2 - S_{12}^2}{(1 - S_{11})^2 - S_{12}^2}.
\]

(7)

As shown in Fig. 4, the characteristic impedance is not exactly 50 ohm in the measurement frequency band. Therefore, a part of the incident wave may be reflected back and forth within the network, building up standing waves. Consequently that may be result in resonances. In reality, the resonance frequency is concerned with the wave length, physical line length, and dielectric constant. In our test, the resonances occur at 7.5GHz and 15GHz for the 5mm long line. Therefore, it can be recognized that the measurement data are meaningful far below 7.5GHz. Thus, we used the s-parameter data up to the 5GHz for the DUT circuit model parameter determination.
C. Circuit Model Parameter Determination

The s-parameter of DUT can be determined by shifting the measurement reference plane. Then converting the s-parameters into ABCD parameters, the circuit model parameters of MLCC are determined by using (4). The circuit model parameters depend upon the frequency are summarized in Table 1. It is noteworthy that the ESR varies with frequency. That means there are other small parasitic reactance components in the test fixture. In reality, there may be parasitic resistance, parasitic capacitance, and parasitic inductance due to the mounting pads on which the MLCC is mounted. However, in this research, these secondary effects are not taken into account. Thus, neglecting the secondary effects, we took the averaged ESL data from 1GHz to 5GHz. In contrast, since the secondary effects become larger as the frequency increases, we took the ESR at the lowest frequency, i.e., 1GHz. The averaged ESLs for nominal 100nF and 10nF MLCCs are 480.7pH and 479.8pH, respectively.

### Table 1. MLCC Circuit Model Parameters

<table>
<thead>
<tr>
<th>Frequency (GHz)</th>
<th>MLCC Type</th>
<th>100nF Re{Z}</th>
<th>Im{Z}</th>
<th>100nF ESL</th>
<th>10nF Re{Z}</th>
<th>Im{Z}</th>
<th>10nF ESL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1GHz</td>
<td>0.130 Ω</td>
<td>2.59 Ω</td>
<td>413.6pH</td>
<td>0.265 Ω</td>
<td>2.42 Ω</td>
<td>387.1pH</td>
<td></td>
</tr>
<tr>
<td>2GHz</td>
<td>0.192 Ω</td>
<td>5.35 Ω</td>
<td>426.6pH</td>
<td>0.382 Ω</td>
<td>5.11 Ω</td>
<td>407.6pH</td>
<td></td>
</tr>
<tr>
<td>3GHz</td>
<td>0.328 Ω</td>
<td>8.61 Ω</td>
<td>456.8pH</td>
<td>0.632 Ω</td>
<td>8.50 Ω</td>
<td>451.4pH</td>
<td></td>
</tr>
<tr>
<td>4GHz</td>
<td>0.625 Ω</td>
<td>12.77 Ω</td>
<td>508.0pH</td>
<td>1.206 Ω</td>
<td>13.12 Ω</td>
<td>522.2pH</td>
<td></td>
</tr>
<tr>
<td>5GHz</td>
<td>1.906 Ω</td>
<td>18.80 Ω</td>
<td>598.6pH</td>
<td>3.346 Ω</td>
<td>19.80 Ω</td>
<td>630.5pH</td>
<td></td>
</tr>
<tr>
<td>Angle</td>
<td></td>
<td></td>
<td>480.7pH</td>
<td></td>
<td></td>
<td>479.7pH</td>
<td></td>
</tr>
</tbody>
</table>

In order to verify the circuit model, s-parameters using the circuit model parameters that are determined in the previous section are determined by using HSPICE simulation. Note, the transmission line circuit model parameters of the access lines are determined from (6) and (7). Then the simulated s-parameters are compared with the measured s-parameters as shown in Fig. 5. The simulated S21 parameter has excellent agreement with the measured one up to 6GHz. In contrast, the simulated S11 parameter has excellent agreement with the measured one up to 3GHz. Thus, the circuit model parameters can be considered valid up to 3GHz. In order to improve the accuracy of the circuit model, the secondary effects need to be considered.
taken into account. However, in many practical applications of MLCCs, it is considered that the 3GHz is high enough.

IV. CONCLUSION

In this research, a new circuit model for an MLCC was developed. A test fixture for the high-frequency characterization for MLCCs is designed. Since the high-frequency s-parameters for an MLCC cannot be accurately measured owing to the parasitic effects due to access lines, the measured s-parameters for the test fixture are de-embedded by using the transmission line characterization techniques. Then from the measured s-parameters, the parasitic circuit model parameters for the MLCC are directly determined. It was shown that the proposed circuit model has excellent agreement with the measured data up to 3GHz.

REFERENCES