Signal Integrity Analysis of High Speed Channel considering Thermal Distribution

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***Abstract*— In this paper, we analyzed a high speed PCB channel and silicon interposer channel considering thermal distribution. High temperature degrades the signal integrity (SI) performances of channel. Therefore, temperature-dependent SI analysis is essential for channel layout design. However, the previous temperature-dependent SI analysis is focused on constant temperature, while it gives less attention to thermal distributions. Hence, this research analyzed thermal distributions with various mean temperatures and standard deviations effect to insertion loss of channel. By using electromagnetic (EM) simulation, we analyzed the thermal distribution effects on high speed channel SI performances. Temperature-dependent SI analysis showed the thermal distribution contributes to critical SI issues for high speed channels. As a result, it showed the increasing mean temperature of thermal distribution caused SI performance degradation.**

Keywords—High speed channel; insertion loss; PCB; signal integrity; silicon interposer; thermal distribution;

I. INTRODUCTION

Recently, demands for high performance systems are continuously increasing due to the development of artificial intelligence. To meet these trends, a high density, high bandwidth, and small form factor system is required. However, as the density and data speed increase, power density extremely increases. Thermal issues are one of the significant design points in high performance system design [1-2]. Especially, the increased power density causes the high temperature, which can directly affect electrical performance such as signal integrity (SI). Therefore, temperature-dependent SI analysis of high speed channels is required for high performance system.

For temperature-dependent SI analysis of high speed channels, the thermal distribution of the channels is important point because the heat of ICs spreads to the channel. Generally, the loss increases as the temperature increases. High speed channel design without considering operating temperature is expected to be under-engineered. On the other hand, it can be over-engineered when considering the thermal distribution as the uniform maximum value [3-4]. Hence, SI analysis of high speed channels considering thermal distribution is required for the high performance system.

In this paper, we analyzed a high speed channel considering thermal distribution. The target applications of this research are LC dominant and RC dominant high speed channel. For analyzing thermal distribution effects on LC dominant and RC dominant channel, we analyzed PCB channel and silicon interposer channel, respectively. Furthermore, we analyzed both microstrip line (ML) and stripline (SL) to analyzed each temperature effect on SI. For analyzed the mean temperature and standard deviation of thermal distribution effects on channel SI performances, we formulated thermal distribution with using a normal distribution equation. The temperature-dependent insertion loss (IL) was simulated for SI analysis. The results showed the increasing mean temperature of thermal distribution caused SI performance degradation.

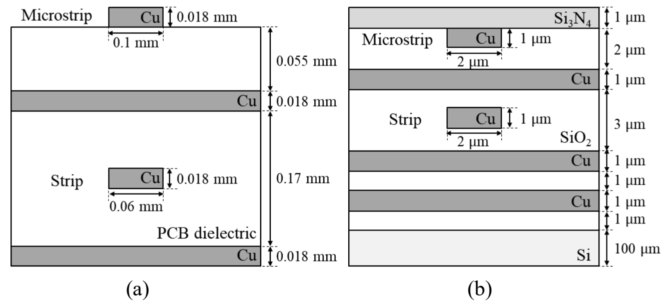

Fig. 1. Designed stack-up of (a) PCB and (b) silicon interposer, and its physical dimensions

TABLE I
TEMPERATURE-DEPENDENT DIELECTRIC PROPERTIES OF PCB DIELECTRIC MATERIAL

	20 ℃	40 ℃	60 ℃	80 ℃	100 ℃
Relative permittivity (ε_r)	4.26	4.28	4.32	4.36	4.40
Loss tangent (tanδ)	0.0184	0.0201	0.0234	0.0256	0.0279

II. MODEL OF HIGH SPEED CHANNEL WITH THERMAL DISTRIBUTION

Fig. 1 depicts the target applications, PCB and silicon interposer's designed stack-up, and its physical dimensions. The length of the designed PCB and silicon interposer channel are 100 mm and 5 mm, respectively. For temperature-dependent SI analysis, we used the temperature-dependent electrical properties of PCB and silicon interposer materials. The PCB dielectric material is standard loss material which written in [5]. Table I represents the temperature-dependent dielectric properties of PCB dielectric material. It showed only a few values, therefore we interpolated those values by linear least square method to obtain the temperature-dependent function of dielectric properties. The silicon interposer materials' temperature-dependent electrical properties, resistivity ρ and relative permittivity ε_r are shown in equation (1), (2), and (3) [6]; Temperature parameter T in Celsius.

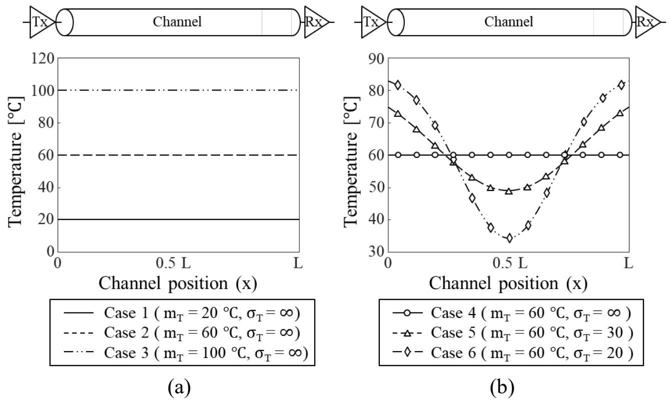

Fig. 2. Case of simulated thermal distributions with (a) various mean temperature and (b) various standard deviation.

$$\rho_{Cu}(T) = \frac{1 + 0.00398 \cdot (T - 26.85)}{58000000} \; [\Omega \cdot m] \tag{1}$$

$$\rho_{Si}(T) = \frac{0.0012T^2 - 0.0352T + 9.976}{100} \; [\Omega \cdot m] \tag{2}$$

$$\varepsilon_{r,ox}(T) = 0.016T + 3.6 \tag{3}$$

For SI analysis considering thermal distribution, we formulated thermal distributions along channel as follows:

$$T(x) = A - B \cdot \frac{1}{\sigma_T \sqrt{2\pi}} exp(-\frac{(x - 0.5 \cdot L)^2}{2 \cdot \sigma_T^2}) \; [°C] \tag{4}$$

Where x is channel position; L is total channel length; σ_T is the standard deviation of thermal distribution. The constant value A and B depend on the value of the mean temperature of thermal distribution m_T. With equation (4), we set 6 cases of thermal distributions as shown in Fig. 2. Those cases are set to analyze SI performances affected by the thermal distribution; Case 1, 2, and 3 are set to analyze the m_T effects on SI; Case 4, 5, and 6 are set to analyze the σ_T effects on SI.

III. TEMEPRATURE-DEPENDENT SIGNAL INTEGRITY ANALYSIS

To analyze the IL of high speed channel, the formula of IL is as follows [7]:

$$IL = e^{-(\alpha + j \cdot \beta)} \tag{5}$$

$$\alpha \approx \frac{R}{2Z_0} + \frac{GZ_0}{2} = \alpha_{cond} + \alpha_{diel} \tag{6}$$

Where α is attenuation constant; β is phase constant; α_{cond} is the attenuation from the conductor loss; α_{diel} is the attenuation from the dielectric loss. α_{cond} is proportional to the metal resistivity, and α_{diel} is proportional to dielectric properties.

A. Signal Integrity Analysis considering Mean Temperature of Thermal Distribution

Fig. 3. (a) shows the IL of high speed PCB channel considering various m_T cases. At low frequency range, due to the PCB channel is LC dominant, the α_{cond} degradation effect is shown small. At high frequency range, due to the PCB dielectric properties have increasing trends along with

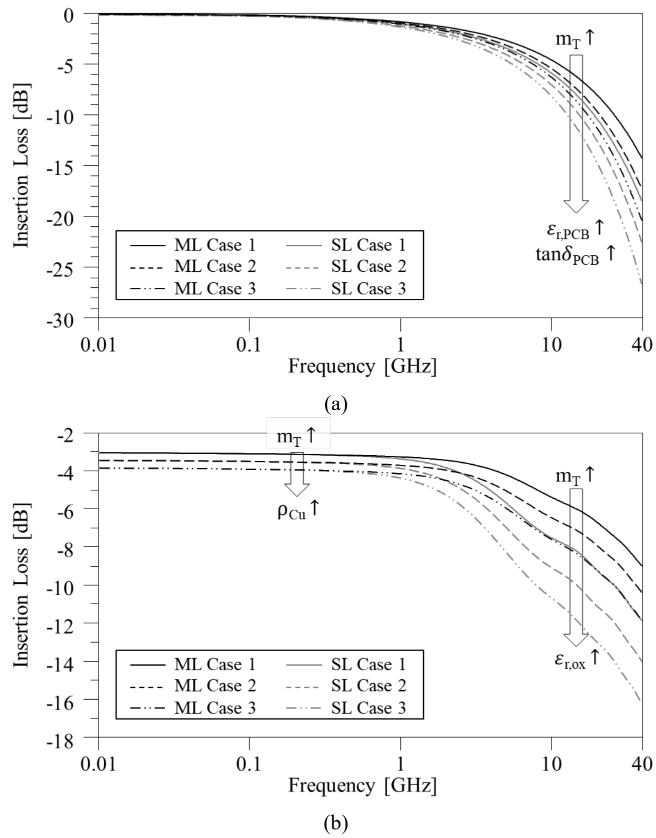

Fig. 3. Simulated insertion loss of high speed (a) PCB channel and (b) silicon interposer channel considering various mean temperature cases

temperature, it showed that increasing temperature causes α_{diel} increasing.

Fig. 3. (b) depicts the IL of silicon interposer channel considering various m_T cases. At low frequency range, due to the silicon interposer channel is RC dominant, the higher copper resistivity as increased temperature causes α_{cond} increasing. Furthermore, at high frequency range, the higher relative permittivity of silicon dioxide caused increasing α_{diel}. Therefore, the high m_T caused increasing IL of the high speed channel.

At low frequency region, IL increase rate due to the temperature increasing, there is no difference between ML and SL. However, at high frequency region, SL has a larger IL increase rate with temperature than ML. Because, as the equation (6), α_{diel} is proportional to conductance. Conductance is proportional to capacitance, which is proportional to ε_r. SL has more ground area compared to ML. Therefore the conductance increasing effects due to the increase in dielectric properties with higher temperature is larger on SL than ML.

Fig. 4 shows the differences of high speed channel IL between 40 °C m_T difference cases at broad frequency. IL differences of both PCB and silicon interposer channel show quite similar values over the broad frequency. In other words, the dB scale IL tends to increase linearly with temperature. Hence, with the equation (5), the temperature and α have a linear function relationship.

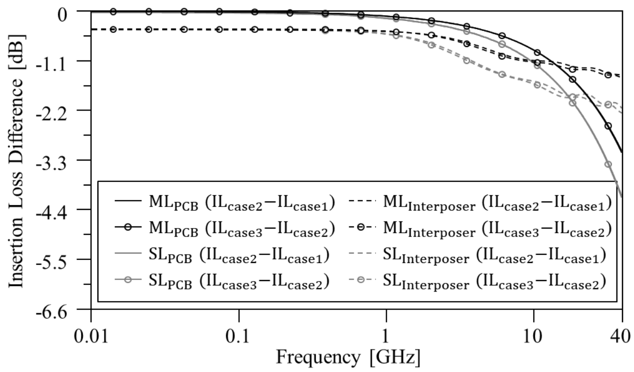

Fig. 4. Difference of simulated high speed channel insertion loss between 40℃ difference cases

B. Signal Integrity Analysis considering Standard Deviation of Thermal Distribution

To analyze the IL considering thermal distribution with various σ_T, we simulated numerous segment channels considering each temperature along thermal distribution, and cascaded them.

$$\alpha_{cascaded} \approx \sum \alpha_{segment} \tag{7}$$

$$\sum_{i=1}^{N} \alpha\left(T_{segment_i}\right) \approx N\,\alpha\left(\frac{1}{N}\sum_{i=1}^{N} T_{segment_i}\right) \tag{8}$$

Where $\alpha_{cascaded}$ is cascaded α; $\alpha_{segment}$ is α of segment channel; $T_{segement}$ is temperature of segment channel; N is amount of segment channel. The $\alpha_{cascaded}$ is a form of the summation of $\alpha_{segment}$ [8-9]. As mentioned earlier, the temperature and α has a linear function relationship. Therefore, as the equation (7) and (8), cascaded α considering thermal distribution is quite similar with α considering mean temperature of thermal distribution.

As shown in Fig. 5, IL of both PCB and silicon interposer channels is not significantly affected by the various σ_T. Even if the σ_T is different at each cases, the effective α is quite similar with same m_T and infinite σ_T case. Therefore, it is sufficient to only consider the m_T for temperature-dependent IL analysis of channel, without considering the σ_T.

IV. Conclusion

In this paper, we analyzed a high speed channel considering thermal distributions. It showed the increasing mean temperature causes SI performance degradation. Furthermore, even if the standard deviation is different, it showed the quite similar insertion loss with same mean temperature case because the temperature and insertion loss have linear function relationship. This research showed that SI analysis considering operating thermal distribution is required for designing high performance system. In addition, when designing the RC dominant channel and stripline channel, it needs more attention to thermal distribution effects on SI performances rather than designing the LC dominant channel and microstrip channel.

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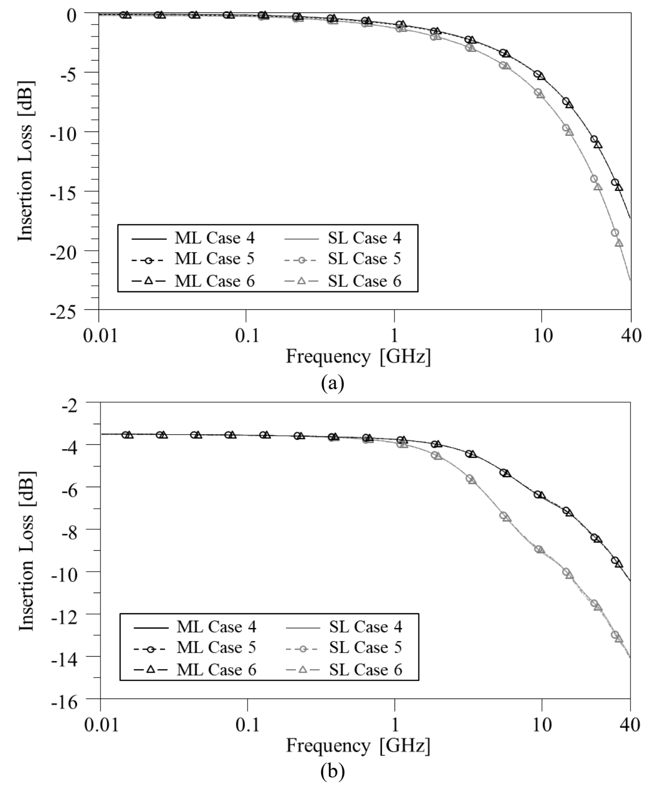

Fig. 5. Simulated insertion loss of high speed (a) PCB channel and (b) silicon interposer channel considering various temperature standard deviation cases

References

[1] K. Son et al., "A Novel Through Mold Plate (TMP) for Signal and Thermal Integrity Improvement of High Bandwidth Memory (HBM)," 2020 IEEE MTT-S International Conference on Numerical Electromagnetic and Multiphysics Modeling and Optimization (NEMO), 2020, pp. 1-4

[2] K. Son et al., "Design and Analysis of Thermal Transmission Line based Embedded Cooling Structures for High Bandwidth Memory Module and 2.5D/3D ICs," 2020 IEEE Electrical Design of Advanced Packaging and Systems (EDAPS), 2020, pp. 1-3

[3] S. Pathania et al., "Thermal Impact on High Speed PCB Interconnects," 2019 IEEE 28th Conference on Electrical Performance of Electronic Packaging and Systems (EPEPS), 2019, pp. 1-3

[4] S. Pathania et al., "Multiphysics Approach Using Computational Fluid Dynamics for Signal Integrity Analysis in High Speed Serial Links," 2019 Electrical Design of Advanced Packaging and Systems (EDAPS), 2019, pp. 1-3

[5] Jim Lai and Tristan Lin, "System operating environment effect on PCB material electrical property," 2016 Asia-Pacific International Symposium on Electromagnetic Compatibility (APEMC), 2016, pp. 314-316

[6] M. Lee et al., "Temperature-dependent through-silicon via (TSV) model and noise coupling," 2011 IEEE 20th Conference on Electrical Performance of Electronic Packaging and Systems, 2011, pp. 247-250

[7] E. Bogatin, Signal and Power Integrity-Simplified. 2nd ed. Englewood Cliffs, NJ: Prentice-Hall, Jul. 2009

[8] A. A. Bhatti, “A computer based method for computing the ndimensional generalized abcd parameter matrices of n-dimensional systems with distributed parameters,” in 22nd Southeastern Symposium on System Theory (SSST) Conference, pp. 590–593, 1990.

[9] David Thorson, “A Review of ABCD Parameter”. Applied Microwave & Wireless, pp.55-58, 1999