Application of Simulation Technology to the Development of High-Speed Electronics

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As the signal processing speed of electronic devices increases, transmission capability over 10 Gbps has been required for printed wiring boards. As electronic equipment has reduced in size and advanced in processing speed, the heat density of such equipment has increased. As high accuracy is required for the integrity of several Gbps signals, we have combined the three-dimensional electromagnetic-field simulation with the signal integrity simulation. In the thermal simulations, we have increased the accuracy of the simulation by external environment reproduction, transient simulation and the modeling of the copper patterns for printed wiring boards. Thus, we have built the optimal solution that meets the product specification. This paper describes the latest simulation technologies (signal integrity, EMC, three-dimensional electromagnetic-field analysis, and thermal simulation) along with some examples of product designs.

Keywords: simulation, gigabit transmission, signal integrity, EMC, 3-D electromagnetic-field simulation, thermal design, electronic equipment

1. Introduction

As the signal processing speed of electronic devices increases, transmission capability over 10 Gbps has been required for printed wiring boards (PWBs). As electronic equipment has reduced in size and advanced in processing speed, the heat density[*1] of such equipment has increased. As high accuracy is required for the signal integrity of several Gbps signals, we have combined the 3-D electromagnetic-field simulation with the signal integrity simulation. In the thermal simulations, we have increased the accuracy by conducting external environment reproduction, transient simulation, and the modeling of copper traces for printed wiring boards (PWBs). Thus, we have built the optimal solution that meets the product specification. This paper describes the latest simulation technologies (signal integrity, EMC, 3-D electromagnetic-field analysis, and thermal simulation) along with some examples of product designs.

2. Advantages of Our Design Methods

The Equipment Development Division, a business unit of Sumitomo Electric System Solutions Co., Ltd., develops and designs electronic equipments. It employs the concurrent design process that includes system/circuit design, application specific integrated circuit/field-programmable gate array (ASIC/FPGA) design, PWB design, and case/mechanical design. In each design step, we use the "simulation-based design" method to optimize the signal integrity, electromagnetic compatibility (EMC[*2]), thermal dissipation, and structure of a product (**Fig. 1**).

In product development, we use both the concurrent design techniques and the simulation-based design method to shorten the design process time, reduce cycles of trial products, and improve the final design quality.

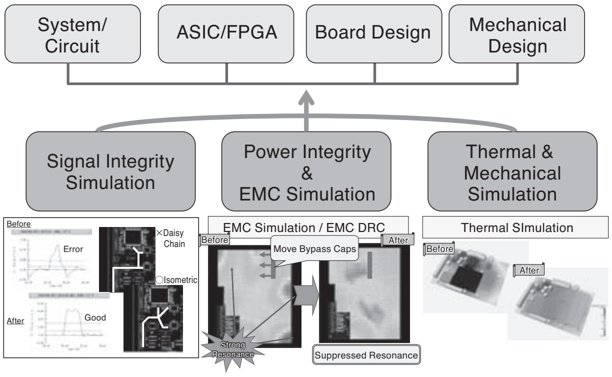


Fig. 1. Simulation-based design method

3. Simulation Application Examples

3-1 Applications of signal integrity and EMC design processes

As application examples of the EMC design process and signal integrity, we report on the design of a 10 Gbps transmission board, which was developed by the Information & Communications Labs in 2007. In this project, we were in charge of PWB design.

The block diagram of the circuit is shown in **Fig. 2**.

① 8 pairs of 3.125 Gbps differential signals (TX, RX)

② 2 pairs of 10 Gbps differential signals (TX, RX)

Therefore, two sets of 10 Gbps transmission paths are configured.

For this FPGA, the power circuit requires 1.0 V (±50 mV) and 15 A, necessitating a difficult board design.

③ A high-current and low-voltage power plane design.

To address these issues, we used the HSPICE simulation, which can provide more accurate results than the IBIS model simulation, in the signal integrity analysis. More-

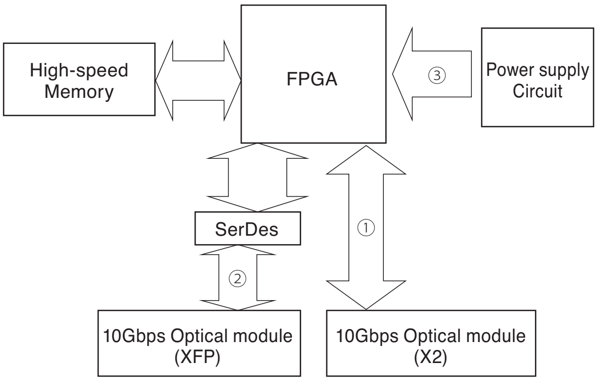


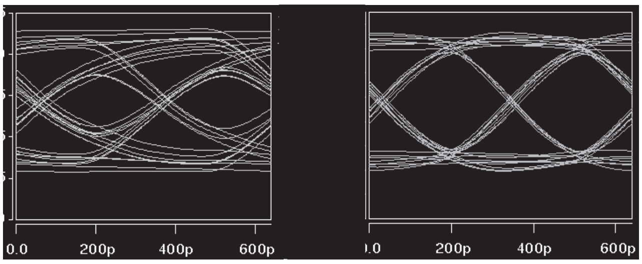
Fig. 2. Block diagram of the 10 Gbps transmission board

over, in order to reduce the power supply noise, we used the power plain resonance analysis along with the expertise of EMC designers. As a result, problems were addressed properly at each step and the accuracy of the EMC design process was improved.

(1) PWB design for over 10 Gbps transmission

It is important for a designer to consider the pre-emphasis of driven signal on device, impedance control, and reduction of high frequency transmission loss in the PWB design for high-speed transmission over Gbps.

Excessive pre-emphasis causes ringing or overshooting, and signal integrity is deteriorated. Therefore, by using the HSPICE simulation, we determined the strength of the optimal pre-emphasis **Fig. 3**.



(a) Pre-emphasis (minimum) **(b) Pre-emphasis (optimal)**

Fig. 3. Pre-emphasis optimization using simulation

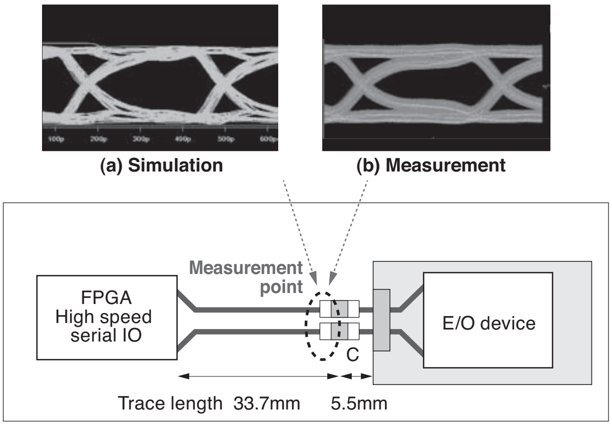
In addition, we improved the transmission characteristics of the vias (through the hole for connecting signals of different signal layers) by placing the GND vias on the outside of signal vias (G-S-S-G structure). In this formation, the return paths are configured and the impedance mismatching is reduced.

Based on our know-how and measures described above, we provided design guidelines as listed below.

- The length of the two differential pair signals must be matched.
- Each TX and RX pair signal of 3.125 Gbps must be routed in the same layer .
- The length of the pair signals in each layer must be matched.
- 3.125 Gbps signals must be routed in two vias or less.
- The Vias of 3.125 Gbps signals must have a G-S-S-G structure.
- 10 Gbps pair signals must be shortest and routed in the microstrip structure on the top layers.

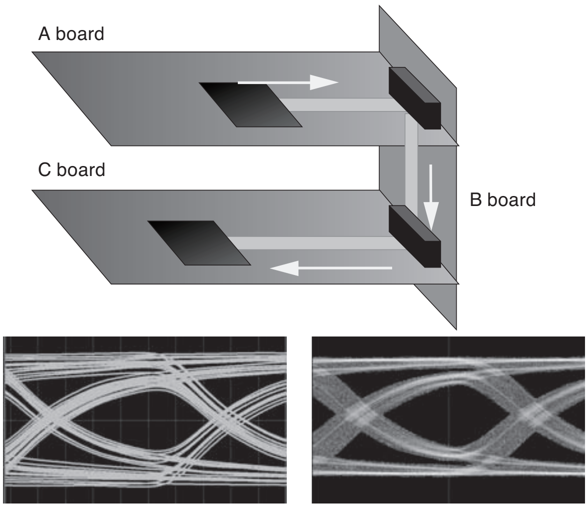
Figure 4 shows a comparison between the measurement results and the simulation results of 3.125 Gbps signals. The waveforms (a) and (b) are very similar, indicating that the accuracy of the simulation is high.

At present, in order to improve the simulation practically enough accuracy, we use the S parameter[*3] model based on 3-D electromagnetic analysis. Thus, as shown in **Fig. 5**, simulation results of 3.125 Gbps signals through three PWBs are similar to the measured results.



(c) Measurement point

Fig. 4. Comparison between experimental and simulation results



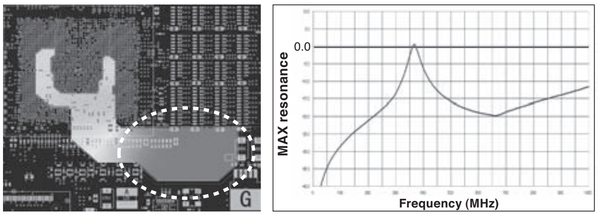
(a) Simulation **(b) Measurement**

Fig. 5. Comparison of 3.125 Gbps signals through three PWBs

(2) EMC design processes

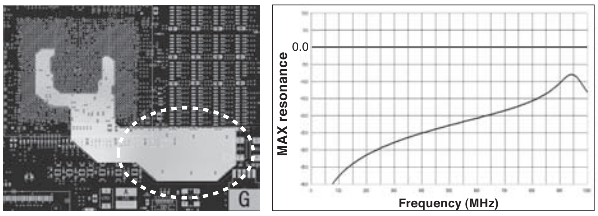
In the EMC design process, we adopted EMC design rules and improved the power quality.

First, we set up design guides, considering the IR drop and the reduction of impedance by a bypass capacitor for the high-current and low-voltage power plane design that meets the MAX ±50 mV specification. Additionally, in order to reduce EMC noise, we conducted the power plane resonance simulation using DEMITASNX after the PWB design. **Fig. 6** and **Fig. 7** show the examples.



(a) Resonance point **(b) noise level**

Fig. 6. Power plane resonance simulation (before)



(a) Resonance point **(b) noise level**

Fig. 7. Power plane resonance simulation (after)

These figures show the results of resonance simulation. In **Fig. 7 (a)**, a greater resonance noise level appears in a darker color. **Figure 7 (b)** shows the spectra of the resonance noise level. Resonance noise of a portion enclosed by the dotted line in **Fig. 6 (a)** is large, but by adding bypass capacitors, the noise level was reduced. By visualizing the effects using tools, we have made the EMC design effective.

(3) Summary of PWB design for over 10 Gbps transmission

In a difficult PWB design process for multiple power planes and signal transmission of over 1 Gbps, by designing using appropriate tools, all functions were operated in the first prototype. In addition, the design period was shortened to 3.5 months and the evaluation period was less than 2 months, which are relatively fast to complete a new board development of this volume. It is considered that the transmission rate will be even higher in the future. A 100 Gbps transmission board will require approximately 20 pairs (TX, RX) of 10 Gbps signal paths. Therefore, issues of noise, transmission loss, and timing adjustment are expected to become more apparent. In order to solve these problems, we will actively promote technology development, such as the introduction of the power integrity simulation and improvement of the simulation model accuracy, and apply these technologies to our product designs.

3-2 Applications of electromagnetic simulation to optical receivers

Optical receivers are important components that convert optical signals into electric signals and used in optical communication systems that connect network devices. The optical receiver used in this study employs a transimpedance amplifier (TIA). **Figure 8** shows a simplified configuration diagram of the receiver. Optical signals are received with a photodiode (PD) and converted into minute current signals, and further converted into voltage signals after amplified by the TIA.

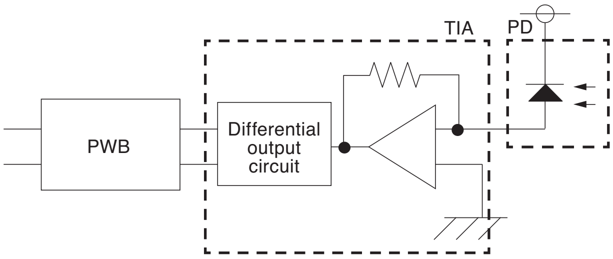


Fig. 8. Simplified configuration diagram of the optical receiver

Figure 9 shows the internal arrangement image of each part. These parts are connected to each other with bonding wire. Power supply pins penetrate the wall to the inside of the case and are also connected to respective parts with bonding wire. A PD is placed on the substrate called PD carrier.

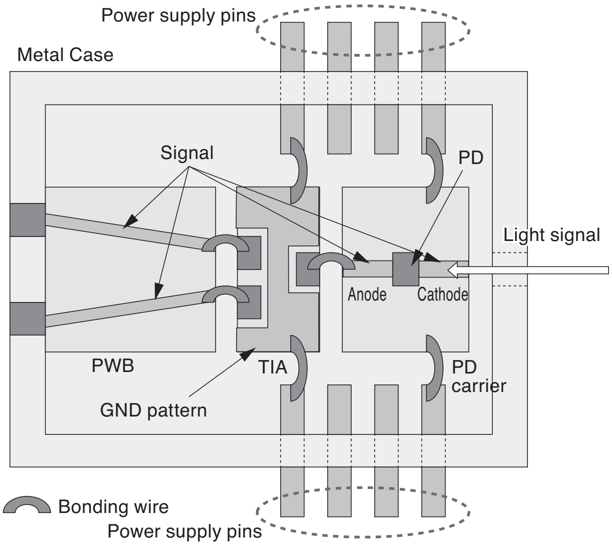


Fig. 9. Internal arrangement image of each part

The PD carrier has a pattern connected to the anode side and the cathode side of the PD. The anode side is connected to the input pad of TIA via bonding wire, whereas the cathode side is connected to the ground via a capacitor. Transimpedance (Zt) is used as a parameter that evaluates the characteristics of this optical receiver. Zt means the ratio at which the input current to TIA is output as a voltage. The goal of the analysis is to obtain an ideal Zt for characteristics improvement.

An optical receiver to which the electromagnetic field simulation was applied showed unfavorable peaks in Zt characteristics. We have built simulation models based on the measurement results, and then examined improvement ideas by using these models.

(1) Problem with actual sample

Figure 10 shows measured Zt characteristics of an actual sample. Unfavorable peaks observed in the frequency band from 17 GHz to 22 GHz. We first reproduced these peaks in simulation.

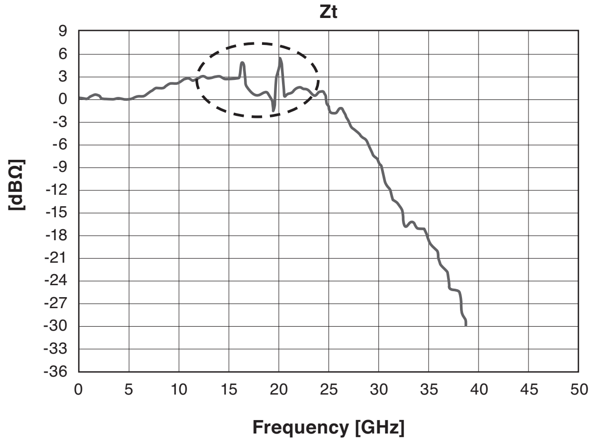


Fig. 10. Zt measurement result with an actual sample

(2) Building a simulation model and calculating the frequency response

To build a simulation model, DXF data was converted into 3-D data by using 3-D CAD technology. The simulation model was built to resemble the actual structure. We analyzed the electromagnetic field by using this model as an initial model and obtained the frequency response.

In this study, we used a 3-D electromagnetic high frequency structure simulator (HFSS), adopting the finite element method (FEM)[*4]. Generally in FEM, simulation time increases according to the number of elements. We applied modification to simulation model with regard to the following two points to shorten the simulation time.

① Using square shapes for a cross-section of bonding wire and a via hole instead of round.
The number of elements increases when round-shaped portions are included. To reduce the number of elements, every round-shaped portion, including the bonding wire cross-section and via hole, was changed to square shaped.

② The thickness of a conductor is ignored, and only skin effects are considered.
The thickness of the thinnest conductor used in this model is 2.3 um, which is very thin compared with the whole model dimension. The number of the elements around the conductor increases when such a thin conductor is used for modeling as it is. Therefore, we considered using the model which allows us to ignore the thickness of the conductor. Generally, skin effects are generated, as high frequency current passes the conductor. That is, the current passes only the surface of the conductor, and hardly passes the inside. When it comes to the conductor with the skin depth of 1/2 or less of the conductor thickness, the conductivity is obtained only by the skin effect. Therefore, conductivity can be realized in the seat form without considering the thickness. In this simulation, the skin depth is equal to 1/2 of the thickness of the conductor when the frequency is at 5 GHz, and therefore the thickness of the conductor can be ignored.
In this model, because the frequency band to be considered is 17 GHz or higher, the conductor thickness can be also ignored. Thus, the number of the elements was remarkably reduced.

As shown in **Table 1**, simulation time was shortened by 90% due to the improvements described above.

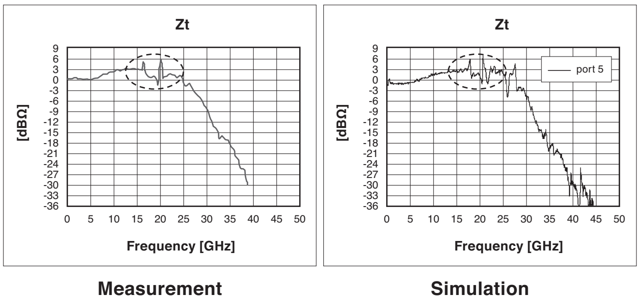
Table 1. Shortening simulation time

	Number of meshes	Memory Used [GB]	Simulation time ratio [*1]
Before applying ①, ②	500k	11.4	1.0
After applying ①, ②	100k	1.1	0.1

[*1] The simulation time ratio refers to the ratio in comparison with the simulation time before ① and ② are applied.

(3) Calculation of Zt

The frequency response obtained by the process described in (2) is regarded as an S parameter model, and Zt is calculated by using a transmission line simulation tool.



Measurement **Simulation**

Fig. 11. Zt characteristics of the initial model

Figure 11 shows the results. In the simulation, the unwanted peaks and dips seen with the actual sample in the frequency band of 17-22 GHz were reproduced. We examined the improvement idea based on this initial model.

(4) Examination of Zt improvement strategy

To investigate the cause of the unwanted peaks and dips in Zt characteristics, the electromagnetic field distribution and the current density of each part were examined. However, no apparent defect was found. Therefore, we carried out the investigation by comparing changes in Zt characteristics associated with changing model shapes. The results show that when the shape of the cathode side pattern of the PD carrier is modified, the characteristic disorder in the area of 17-22 GHz is improved. The simulation result of Zt characteristics using the improved model is shown in **Fig. 12**.

Small dips are still observed in **Fig. 12**. We conclude that this small dips are due to the resonance caused by the parasitic components on the capacitors which were added to the model to improve the Zt characteristics. The parasitic components were generated due to the single-layer structure of the simulation model. These factors are suppressed with the actual capacitor which has a multi- (not single) layer structure, and therefore, the small dips observed in **Fig. 12** should not occur in the actual sample. We reviewed all the above-mentioned results with the members in the Transmission Devices R&D Laboratories to design an improved model.

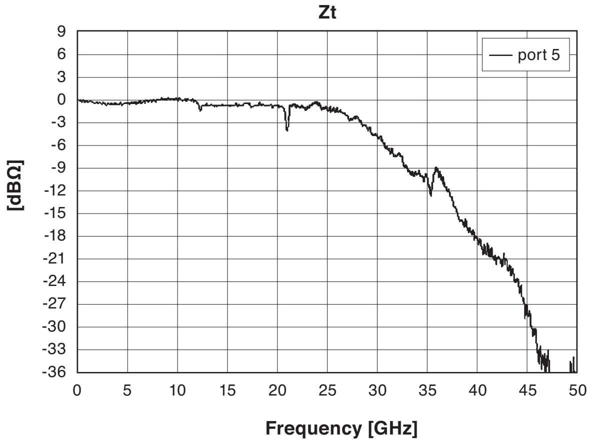


Fig. 12. The simulation result of Zt characteristics of the improved model

(5) Result

Figure 13 shows the measurement result of the improved actual sample. The unfavorable peaks and dips seen in the frequency band of 17-22 GHz have been suppressed to the similar level seen in the simulation result. As the improvement of TIA has been promoted at the same time, Zt characteristics have also been improved at 25 GHz or higher frequency compared with the result shown in **Fig. 12**.

In this study, we investigated the cause of the unfavorable peaks and dips seen in Zt characteristics, and carried out simulations by using a revised design to improve the characteristics of the actual sample. As a result, we have established a simulation method of applying the electromagnetic field simulation to optical receiver design. In this simulation method, we have advantages in considering improvement models, particularly in verifying characteristics of various structures by combining several kinds of analyses.

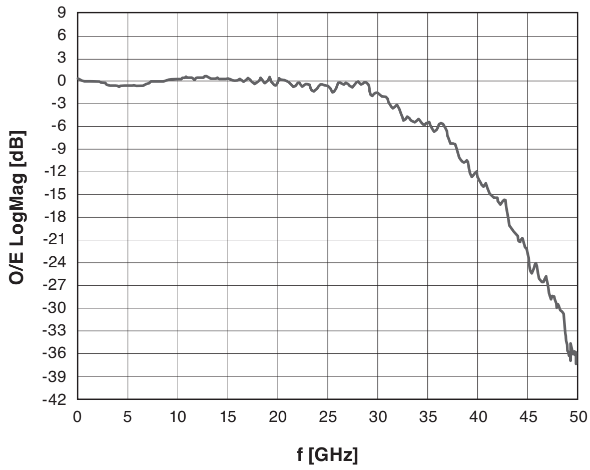


Fig. 13. Measurement result of the improved actual sample

3-3 Examples of thermal design

The latest thermal design examples are described in this chapter.

(1) Thermal simulation with copper trace model

Generally, PWBs have multilayered structures, and different copper trace patterns are formed on each layer. In general, a PWB is modeled as a material of an equivalent thermal conductivity by synthesizing copper traces and glass-epoxy insulation layers. However, in the case that a large current flows on copper trace, more detailed simulation models are needed. The purpose is to calculate the heat radiation by the conduction of heat from electronic parts mounted on the PWB, and there are three reasons for this attempt. ① In the case that miniaturized electronic equipment cannot accommodate a large heat sink, copper trace of the PWB is an important heat-conducting route. ②As heat generating components tend to be miniaturized, their surface areas decrease and the heat released to the PWB relatively increases. Then the heat radiation to the air decreases. ③ As more electronic equipment has a large current, in many cases joule heat generated on copper trace becomes unignorable. In addition, the design using simulation tools has become common. Therefore, we have provided simulation results improved in accuracy.

To take a PWB as an example, four types of models are prepared, as shown in **Table 2**, to select a model suitable for each case. The feature of each model is as follows:

A: a model based on the assumption that the PWB has a synthetic thermal conductivity

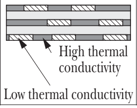
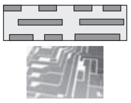
B: a model with the copper foil occupancy ratio set for each layer.

C: a model for which the wiring density of each layer is reproduced.

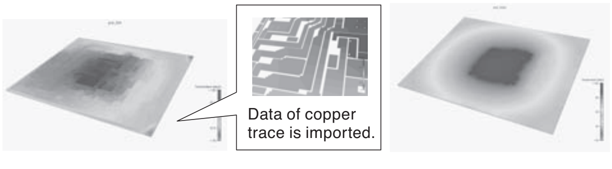
D: a model for which the copper trace pattern of each layer is considered.

As the design advances, the models shift B→C→D after model A is used at the initial design stage. The model A has a computable advantage in a short time. However, the error margin factor of the simulation tends to be larger. On the other hand, the model D requires longer simulation time but the simulation accuracy is higher than the others. These models are selectively used depending on the purpose of the simulation.

Table 2. PWB thermal simulation model

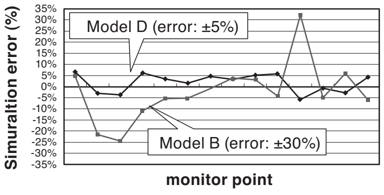
	A	B	C	D
Model	Uniform thermal conductivity	FR4 + Uniform thermal conductivity for each layer	FR4 + high or low thermal conductivity for each layer	FR4 + copper trace
Image				
Lead Time	Short →			Long
Precision	Low →			High
Process	Concept design →			Detailed design

The detailed simulation results of an actual example using a copper trace model is shown in **Fig. 14**. In (a), copper traces are modeled and the joule heat from a large current is considered. On the other hand, in (b), joule heat trace distribution is not considered. Temperature distribution results of (a) and (b) are quite different. As shown in (c), measured temperature distribution is similar in (a) rather than in (b). The result shows a detailed modeling of copper traces and brings more accurate simulation results.



(a) Temperature distribution on the model D (with modeling for copper trace)

(b) Temperture distribution on the model B (without modeling for copper trace)



(c) Simuraltion error (models B and D)

Fig. 14. Modeling example of copper trace

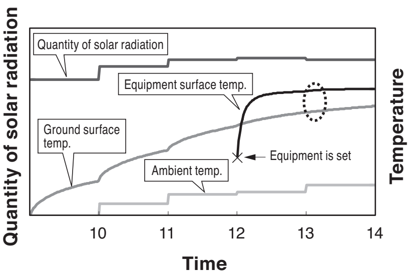
As model D resembles the actual PWB and the distributed heat source is quite different from those of A-C, the simulation error margin of D becomes small when a large current flows and joule heat generation is disregarded. For instance, the error margin with the measured result is 5% with model D, while it is ±30% with model B. Moreover, the best PWB structure is examined by this approach, and it is possible to feed it back to the PWB design. Thus, the improvement of design precision is expected by obtaining a highly accurate calculation result.

(2) Transient analysis*5 considering solar radiation effects

In recent years, electronic equipment installed outdoors increases with the development of communication networks and photovoltaic power generation devices. The electronic equipment used indoors can meet specifications through the inspection of a temperature rise caused by the heat of the equipment itself. But, for electronic equipment installed outdoors, solar radiation (sunlight) should also be considered.

In this section, a typical case that the effect of solar radiation is under discussion.

In this case, this product is installed on the ground and left for about one hour. Additionally, it was required to predict the temperature rise in summer using computer simulation, because the temperature evaluation of the prototype was carried out in the season of weak sunlight. At first, we compared the calculated result with the measurement result obtained by using the prototype equipment placed on the ground. We used simulation tools that calculate the quantity of solar radiation by setting latitude and longitude. The measurement result is: (surface temperature of the equipment's top side) > (surface temperature



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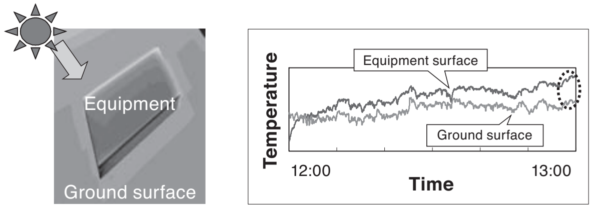
(a) Result of simulation



(b) Temperature distribution (results of simulation)

(c) Temperature measurement

result of simulation ≒ result of temperature measurement

⬚ in (a) corresponds the same area in (c)

Fig. 15. Example of transient analysis (solar radiation effects)

of the equipment's bottom side). The calculated result is: (surface temperature of the equipment's top side) < (surface temperature of the equipment's bottom side). These results show the different tendency. In calculation, the surface temperature of the bottom side of the equipment is higher than that of the top side. As the prototype is painted with a low solar radiation absorption[*4] material, the bottom of the equipment is heated by the ground heat. In the traditional steady analysis, we cannot avoid this phenomenon. We concluded that the calorific capacity of the experimental model is small and it will be in a steady state in about one hour, but the ground, whose calorific capacity is large, has not reached a steady state. Therefore, we decided to apply the transient analysis instead of the traditional steady analysis (**Fig. 15**).

As a result, the simulated temperature rise for the equipment kept outside for one hour after the installation at noon was in agreement with the actual measured result, and the temperature distribution both on top and bottom sides was also identical. We predicted the annual maximum temperature with this simulation method by setting summer temperature and solar radiation. We came to a conclusion that there is no thermal problem in using simulation results for the actual measured value. In fact, we confirmed that there is no problem in the actual temperature rise test conducted in the summer season. This demonstrates that the mass-production sample of this simulation technique is of service. This simulation model enables us to develop products without waiting for test results of summer season and shortens the development process.

4. Simulation Technology Trends in the Future

Electronic devices are expected to increasingly advance in transmission speed and reduce in size and weight in the future. The optical transmission speed has already reached 100 Gbps, and it is necessary to work on technical development with the view of 400 Gbps transmission. For the 100 Gbps transmission, a method of bundling approximately 20 pairs of transmission paths of over 10 Gbps is currently used, but a method of implementing approximately 8 pairs of paths of about 25 Gbps is also considered. In a 400 Gbps transmission board, a transmission rate of over 25 Gbps is essential, and FPGA with a transmission rate of 28 Gbps has also been on the market. From this perspective, it is assumed that simulation is essential for board design.

To create lightweight and compact equipment, metal-based cases have been replaced with plastic cases. Therefore, in the thermal management and EMC design, measures by heat sink or metal shield cannot be used. In this way, simulation becomes more important for thermal management and EMC design.

With respect to these issues, we will keep working on technological development, while flexibly responding to the latest market needs and technology trends.

5. Conclusion

In this report, we have summarized our former four reports on simulation-based design achievements. We also discussed availabilities and features of our simulation methods, and then considered technical trends and our challenges to be addressed in the future.

Today, a signal transmission rate of over Gigabit is required in various fields including the ICT equipment, automotive, and medical industries. In these circumstances, wide varieties of advanced design technologies are needed for size and weight reduction of equipment.

For the future, we will continuously brush up our simulation methods of signal integrity, EMC & noise, thermal control, and strength improvement. At the same time, we will contribute to network equipment development of the Sumitomo Electric Group, providing design solutions for higher speed and higher-capacity transmission by using our unique concurrent design methods, simulation technologies, and expertise on PWB design and mechanical design.

Technical Terms

*1 Heat density: A unit that indicates the value of generated heat per unit volume. Heat density = total power dissipation/volume of equipment

*2 EMC: Electro magnetic compatibility (EMC) aims to ensure that equipment or a system will prevent electromagnetic interference from other equipment.

*3 S-parameters: Scattering parameters (S-parameters), the elements of an scattering matrix or S-matrix, describe the electrical behavior of linear electrical networks when undergoing various steady state stimuli by electrical signals.

*4 FEM: In the finite element method (FEM), solid entities are sliced to small pieces (elements) as a tetrahedron or rectangular solid. To model curved faces smoothly, smaller elements are needed for more accurate results, however, smaller elements cause an increase in the number of elements, resulting in an increase in calculation time.

*5 Transient analysis: A calculation technique for the temperature change by the transitional phenomenon.

*6 Ratio of solar radiation absorption: A ratio of sunbeam energy absorbed by a housing surface.

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