Multi-GPU based Fast Electromagnetic Simulation Method for Analysing PCB

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***Abstract*—This paper describes the efficiency of the fast electromagnetic simulation method for analysing the PCBs. This method is constructed by combination of the multi graphics processing unit (GPU) systems and the weakly conditionally stable algorithms. The weakly conditionally method is faster than the conventional ones in the case of fine cell including the computational domain. In addition, this method is suitable for parallel implementation with multi-GPU computing. First, the weakly conditionally stable algorithm is described briefly. Second, this method is shown. Finally, the efficiency of the multi-GPU based method is verified by analysing an example of the practical PCB.**

I. Introduction

The finite-difference time-domain (FDTD) method [1] is one of the simulation techniques to solve electromagnetic problems. The FDTD method is based on the explicit finite difference method. Thus, the time step size must be less than the one based on the Courant-Friedrichs-Lewy (CFL) condition when this method is used. The maximum time step size is dependent on the minimum cell size in a computational domain. In order to analyze electromagnetic problems which are including fine cell in the computational domain such as the printed circuit boards (PCBs), the FDTD method requires the huge computing resources. Therefore, the fast simulator is strongly demanded.

The weakly conditionally simulation technique, which is the hybrid implicit-explicit (HIE)-FDTD method, has been proposed and studied for the fast electromagnetic field simulation [2]–[4]. The maximum time step size for the HIE-FDTD method can be larger than that for the FDTD method. This method is suitable for the parallel implementation, thus the MPI-based parallel-distributed HIE-FDTD method [5] and the general purpose computing on graphics processing units (GPGPU)-based HIE-FDTD method [6] have been proposed. In addition, the multi-GPU based HIE-FDTD method has been proposed, which is constructed by combination of these simulation techniques [7], [8].

In this paper, the efficiency of the multi-GPU based HIE-FDTD method is described for fast electromagnetic simulations of PCBs. First, the HIE-FDTD method is reviewed briefly. Next, the Multi-GPU based HIE-FDTD method is described. Finally, the efficiency of this method is evaluated through numerical results.

II. HIE-FDTD method

The HIE-FDTD method has been proposed for the efficient electromagnetic simulation of the given object with thin cell sizes in the computational domain such as layer of PCBs. Here, it is assumed that the fine dimension is along the z direction. In such a case, E_z and H_z components are applied to the explicit finite difference method. Due to E_z and H_z components do not contain the derivatives with respect to z. First, the updating formulas of E_z and H_z components are given by,

$$\begin{aligned}E_z^{n+\frac{1}{2}}\left(i,j,k+\frac{1}{2}\right)&=C_a\left(i,j,k+\frac{1}{2}\right)E_z^{n-\frac{1}{2}}\left(i,j,k+\frac{1}{2}\right)\\&+C_b\left(i,j,k+\frac{1}{2}\right)\left\{H_y^n\left(i+\frac{1}{2},j,k+\frac{1}{2}\right)-H_y^n\left(i-\frac{1}{2},j,k+\frac{1}{2}\right)\right\}/\Delta x(i)\\&-C_b\left(i,j,k+\frac{1}{2}\right)\left\{H_x^n\left(i,j+\frac{1}{2},k+\frac{1}{2}\right)-H_x^n\left(i,j-\frac{1}{2},k+\frac{1}{2}\right)\right\}/\Delta y(j),\end{aligned}\tag{1}$$

$$\begin{aligned}H_z^{n+\frac{1}{2}}\left(i+\frac{1}{2},j+\frac{1}{2},k\right)&=H_z^{n-\frac{1}{2}}\left(i+\frac{1}{2},j+\frac{1}{2},k\right)\\&-D_b\left(i+\frac{1}{2},j+\frac{1}{2},k\right)\left\{E_y^n\left(i+1,j+\frac{1}{2},k\right)-E_y^n\left(i,j+\frac{1}{2},k\right)\right\}/\Delta x\left(i+\frac{1}{2}\right)\\&+D_b\left(i+\frac{1}{2},j+\frac{1}{2},k\right)\left\{E_x^n\left(i+\frac{1}{2},j+1,k\right)-E_x^n\left(i+\frac{1}{2},j,k\right)\right\}/\Delta y\left(j+\frac{1}{2}\right),\end{aligned}\tag{2}$$

where

$$C_b(i,j,k)=\frac{2\Delta t}{2\epsilon(i,j,k)+\Delta t\sigma(i,j,k)},D_b(i,j,k)=\frac{\Delta t}{\mu(i,j,k)},$$

and n is the time step index, Δt is the time step size, $\Delta x, \Delta y$ and Δz are the cell sizes along the x, y and z directions, μ, ϵ and σ are permeability, permittivity and conductivity, respectively. The updating formulas of other electromagnetic components can be also expressed by using implicit finite difference method. Here, updating formulas of E_x and H_y are given by (3) and (4). These formulas are shown at the top of next page. The updating formulas of E_y and H_x are similar to the updating formulas of E_x and H_y, respectively.

The maximum time step size for the HIE-FDTD method can be larger than that for the FDTD method. The maximum time step size for the HIE-FDTD method is given by

$$\Delta t_{HIE} \leq \frac{1}{c\sqrt{\left(\Delta x_{min}\right)^{-2}+\left(\Delta y_{min}\right)^{-2}}},\tag{5}$$

$$
\begin{aligned}
&-\alpha E_x^{n+1}\left(i+\frac{1}{2},j,k-1\right)+\beta E_x^{n+1}\left(i+\frac{1}{2},j,k\right)-\gamma E_x^{n+1}\left(i+\frac{1}{2},j,k+1\right)=C_a\left(i+\frac{1}{2},j,k\right)\Big/C_b\left(i,j,k+\frac{1}{2}\right)E_x^{n}\left(i+\frac{1}{2},j,k\right)\\
&+\left\{H_z^{n+\frac{1}{2}}\left(i+\frac{1}{2},j+\frac{1}{2},k\right)-H_z^{n+\frac{1}{2}}\left(i+\frac{1}{2},j-\frac{1}{2},k\right)\right\}\Big/\Delta y(j)-\left\{H_y^{n}\left(i+\frac{1}{2},j,k+\frac{1}{2}\right)-H_y^{n}\left(i+\frac{1}{2},j,k-\frac{1}{2}\right)\right\}\Big/\Delta z(k)\\
&+\frac{D_b\left(i+\frac{1}{2},j,k+\frac{1}{2}\right)}{2\Delta z\left(k\right)}\left\{\left\{E_x^{n}\left(i+\frac{1}{2},j,k+1\right)-E_x^{n}\left(i+\frac{1}{2},j,k\right)\right\}\Big/2\Delta z\left(k+\frac{1}{2}\right)-\left\{E_z^{n+\frac{1}{2}}\left(i+1,j,k+\frac{1}{2}\right)-E_z^{n+\frac{1}{2}}\left(i,j,k+\frac{1}{2}\right)\right\}\Big/\Delta x\left(i+\frac{1}{2}\right)\right\}\\
&-\frac{D_b\left(i+\frac{1}{2},j,k-\frac{1}{2}\right)}{2\Delta z\left(k\right)}\left\{\left\{E_x^{n}\left(i+\frac{1}{2},j,k\right)-E_x^{n}\left(i+\frac{1}{2},j,k-1\right)\right\}\Big/2\Delta z\left(k-\frac{1}{2}\right)-\left\{E_z^{n+\frac{1}{2}}\left(i+1,j,k-\frac{1}{2}\right)-E_z^{n+\frac{1}{2}}\left(i,j,k-\frac{1}{2}\right)\right\}\Big/\Delta x\left(i+\frac{1}{2}\right)\right\},\quad (3)\\
&H_y^{n+1}\left(i+\frac{1}{2},j,k+\frac{1}{2}\right)=H_y^{n}\left(i+\frac{1}{2},j,k+\frac{1}{2}\right)+D_b\left(i+\frac{1}{2},j,k+\frac{1}{2}\right)\left\{E_z^{n+\frac{1}{2}}\left(i+1,j,k+\frac{1}{2}\right)-E_z^{n+\frac{1}{2}}\left(i,j,k+\frac{1}{2}\right)\right\}\Big/\Delta x\left(i+\frac{1}{2}\right)\\
&-D_b\left(i+\frac{1}{2},j,k+\frac{1}{2}\right)\left\{E_x^{n+1}\left(i+\frac{1}{2},j,k+1\right)+E_x^{n}\left(i+\frac{1}{2},j,k+1\right)-E_x^{n+1}\left(i+\frac{1}{2},j,k\right)-E_x^{n}\left(i+\frac{1}{2},j,k\right)\right\}\Big/2\Delta z\left(k+\frac{1}{2}\right),\quad (4)
\end{aligned}
$$

where

$$
C_a\left(i,j,k\right)=\frac{2\epsilon\left(i,j,k\right)-\Delta t\sigma\left(i,j,k\right)}{2\epsilon\left(i,j,k\right)+\Delta t\sigma\left(i,j,k\right)},\alpha=\frac{D_b\left(i+\frac{1}{2},j,k-\frac{1}{2}\right)}{4\Delta z\left(k-\frac{1}{2}\right)\Delta z\left(k\right)},\beta=C_b\left(i+\frac{1}{2},j,k\right)+\frac{D_b\left(i+\frac{1}{2},j,k-\frac{1}{2}\right)}{4\Delta z\left(k-\frac{1}{2}\right)\Delta z\left(k\right)}+\frac{D_b\left(i+\frac{1}{2},j,k+\frac{1}{2}\right)}{4\Delta z\left(k\right)\Delta z\left(k+\frac{1}{2}\right)},
$$

$$
\gamma=\frac{D_b\left(i+\frac{1}{2},j,k+\frac{1}{2}\right)}{4\Delta z\left(k\right)\Delta z\left(k+\frac{1}{2}\right)}.
$$

where Δt_{HIE} is the time step size for the HIE-FDTD method, c is the velocity of light, Δx_{min} and Δy_{min} are the minimum cell sizes along x and y directions.

III. Multi-GPU HIE-FDTD method

The multi-GPU HIE-FDTD method consists of the parallel distributed HIE-FDTD method and the GPGPU-based HIE-FDTD method. Thus, the computational domain is divided into several subdomains and the updating procedures for subdomain are computed by a GPU. In order to use the GPU, each subdomain is partitioned into several blocks. In this section, the domain decomposition techniques and the updating procedures are described.

A. Domain decomposition

The HIE-FDTD method is composed of the four explicit updating procedures and the two implicit updating procedures. In the implicit updating procedures, these are updated by solving the simultaneous linear equations. Generaly, the parallel linear system solver has several overheads. The overall performance is reduced by the overheads. Therefore, the overhead must be minimized for the parallel computing. In order to avoid the overhead, the subdomain is generated by dividing the 3D computational domain along the x and y directions. Here, the number of subdomains is the same as number of GPUs. Note that the boundary cells of subdomain are overlapped with the neighbouring subdomains for communicating the magnetic components between the neighbouring subdomains. In addition, each subdomain is partitioned into several blocks for the GPU computing. In the explicit updating procedures, the subdomain is divided into the blocks which are composed of 64 variables. Fig. 1a shows the divided subdomain for the explicit updating procedures. Each variable is allocated to a thread which compute the updating formula. On the other hand, in the implicit updating procedures, the subdomain is partitioned into the blocks which consist of $64\times NZ$ variables, where NX, NY, and NZ are number of cells for the x, y, and z directions, respectively. Here, $64\times NZ$ variables are assigned to a thread. Fig. 1b illustrates the partitioned subdomain for the implicit updating procedures. Each thread solves the simultaneous linear equations.

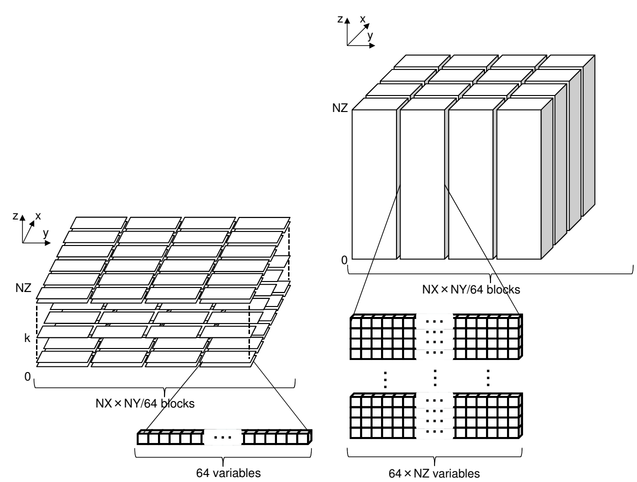

Fig. 1. Divided subdomain. (a) domain partitioning for explicit updating procedures. (b) domain partitioning for implicit updating procedures.

B. Updating procedure

The data communication is one of the overheads of the parallel computing. Here, in order to hide the data communication time, the data communication and computation should be concurrently executed in this method. Fig. 1 illustrates the pseudo-code of this method. From Fig. 1, the values of magnetic components are communicated between the neighboring subdomains by using the non-blocking MPI function. The program can calculate during the data communication. As a result, the sequential processing is minimized in the updating process.

Algorithm 1 Updating procedure

while Current Time $\leq$ Ending Time **do**
  Compute Hz at the boundary part
  Communicate Hz at boundary part between neighbouring part
  Compute Hz except boundary part
  Compute Ez except boundary part
  Wait for completion of Hx and Hy of boundary part communicate
  Compute Ez at boundary part
  Compute Ex and Ey except boundary part
  Wait for completion of Hz at boundary part communicate
  Compute Ex and Ey of boundary part
  Compute Hx and Hy of boundary part
  Communicate Hx and Hy at boundary part between neighbouring part
  Compute Hx and Hy except boundary part
end while

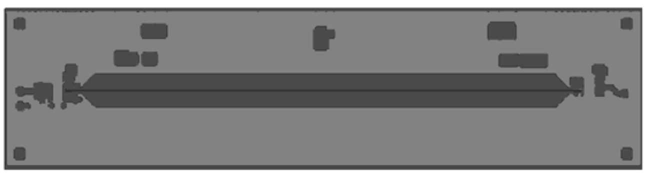

Fig. 2. An example PCB model.

IV. Numerical results

In order to verify the efficiency of the proposed method, the PCB model has been simulated. Fig. 2 shows the simulated PCB configuration. This example has two transmission lines and four layers. A pulse excitation with 0.1 nsec rise/fall time, a width of 0.5 nsec, and an amplitude of 1.0 V was used. The number of cells is $658 \times 194 \times 93 (\approx 1.19 \times 10^7)$. Mur absorbing boundary condition is used. In all of the simulations, Intel Xeon E5-2650 was used for the FDTD method and the HIE-FDTD method and Tesla C2075 was used the multi-GPU HIE-FDTD method. Additionally, 8 GPUs was used in the multi-GPU HIE-FDTD method. Fig. 3 and Table I show the simulation results by the FDTD method, HIE-FDTD method and the multi-GPU HIE-FDTD method. The waveform results show good agreement between these method. From Table I, the multi-GPU HIE-FDTD method is about 1000 times faster than the FDTD method.

V. Conclusion

This paper described the efficiency of the multi-GPU based HIE-FDTD method. From the numerical results, the multi-GPU based HIE-FDTD method is about 1000 times faster than the standard FDTD method.

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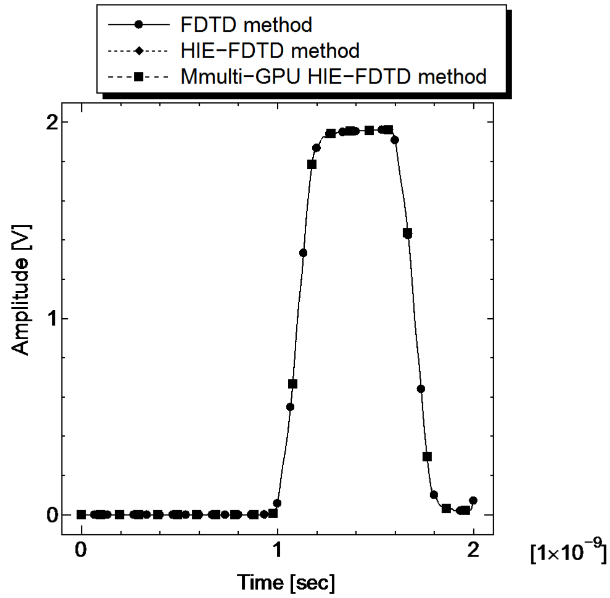

Fig. 3. Simulation results of far end of driven line.

TABLE I
Comparison of execution times by the FDTD method, the HIE-FDTD method and the multi-GPU HIE-FDTD method.

		Number of PEs	Number of Cells 658×194 ×93 cells	speed-up ratio (vs FDTD method)
Elapsed time(sec)	FDTD method	1(CPU)	723668.0	1.0
	HIE-FDTD method	1(CPU)	15896.8	45.5
	multi-GPU HIE-FDTD method	8(GPUs)	703.8	1028.2

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