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GPGPU Based 3D FEM Simulation of SAW Resonators Using Hierarchical Cascading Technique

階層的縦続法と汎用 GPU を組み合わせた SAW 共振子の 3D FEM シミュレーション

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1. Introduction

Nowadays, surface acoustic wave (SAW) devices have been widely used in many different fields especially in the communication system. The Finite Element Method (FEM) has been used for finding appropriate device structures and parameter determination which is necessary for device simulation. However, the conventional FEM was not applicable for whole 3D simulation of SAW devices because of required memory size and computation time.

Solal, et al. pointed out[1] that whole 3D FEM simulation of SAW devices is possible by use of the hierarchical cascading technique (HCT) proposed by Koskela, et al[2]. This is because the HCT can reduce the required memory size and computational time significantly when the device structure under concern is mainly composed of periodic elements. Nevertheless, calculation time reported in [1] was enormous even high-end workstation was used for the calculation.

This paper discusses application of general purpose graphic processor unit (GP-GPU) to SAW device simulation using HCT. It is demonstrated how the powerful GPU is effective for speed up of FEM simulation of full 3D SAW device structures.

2. HCT and Use of GPU

The HCT starts from decomposition of the whole structure into small cells. Let us express the FEM matrix of a unit cell as

$$\begin{pmatrix} \boldsymbol{A}_{\rm LL} & \boldsymbol{A}_{\rm LC} & \boldsymbol{0} \\ \boldsymbol{A}_{\rm LC} & \boldsymbol{A}_{\rm CC} & \boldsymbol{A}_{\rm CR} \\ \boldsymbol{0} & \boldsymbol{A}_{\rm RC} & \boldsymbol{A}_{\rm RR} \end{pmatrix} \begin{pmatrix} \boldsymbol{u}_{\rm L} \\ \boldsymbol{u}_{\rm C} \\ \boldsymbol{u}_{\rm R} \end{pmatrix} = \begin{pmatrix} \boldsymbol{T}_{\rm L} \\ \boldsymbol{0} \\ \boldsymbol{T}_{\rm R} \end{pmatrix}, \qquad (1)$$

where $\boldsymbol{A}_{ij}$ are sub-matrices, $\boldsymbol{u}$ and $\boldsymbol{T}$ are degrees of freedoms (DOFs) and surface forces, respectively, and subscripts R and L indicate values at left and right boundaries, respectively, while the subscript C indicates elsewhere. It Is clear that elimination of $\boldsymbol{u}_{\rm C}$ results in the form of

$$\begin{pmatrix} \boldsymbol{B}_{\rm LL} & \boldsymbol{B}_{\rm LR} \\ \boldsymbol{B}_{\rm RL} & \boldsymbol{B}_{\rm RR} \end{pmatrix} \begin{pmatrix} \boldsymbol{u}_{\rm L} \\ \boldsymbol{u}_{\rm R} \end{pmatrix} = \begin{pmatrix} \boldsymbol{T}_{\rm L} \\ \boldsymbol{T}_{\rm R} \end{pmatrix}. \qquad (2)$$

Next, let us consider the case when two identical unit cells A and B are attached (cascaded). Since $\boldsymbol{u}_{\rm R}^{\rm A}=\boldsymbol{u}_{\rm L}^{\rm B}$ and $\boldsymbol{T}_{\rm R}^{\rm A}+\boldsymbol{T}_{\rm L}^{\rm B}=\boldsymbol{0}$ at the attached boundary, we get

$$\begin{pmatrix} \boldsymbol{B}_{\rm LL} & \boldsymbol{B}_{\rm LR} & \boldsymbol{0} \\ \boldsymbol{B}_{\rm RL} & \boldsymbol{B}_{\rm RR}+\boldsymbol{B}_{\rm LL} & \boldsymbol{B}_{\rm LR} \\ \boldsymbol{0} & \boldsymbol{B}_{\rm RL} & \boldsymbol{B}_{\rm RR} \end{pmatrix} \begin{pmatrix} \boldsymbol{u}_{\rm L}^{\rm A} \\ \boldsymbol{u}_{\rm R}^{\rm A}(=\boldsymbol{u}_{\rm L}^{\rm B}) \\ \boldsymbol{u}_{\rm R}^{\rm B} \end{pmatrix} = \begin{pmatrix} \boldsymbol{T}_{\rm L}^{\rm A} \\ \boldsymbol{0} \\ \boldsymbol{T}_{\rm R}^{\rm B} \end{pmatrix}, \qquad (3)$$

where the superscripts A and B indicate values in cells A and B, respectively. Since Eq. (3) has the same form as Eq. (1), Eq. (3) can be reduced into the same form of Eq. (2). Application of this procedure between to newly generated B matrices, we can obtain the B matrix for cascading four (2^2) cells. Thus, run time for the B matrix calculation increases by N when identical cells are cascaded for 2^N times. Finally, the B matrices for various elements are cascaded, and the whole structure are analyzed using the boundary conditions at the outermost side edges.

This procedure (HCT) can accelerate the calculation speed significantly when the structure under concern is mainly composed of many identical cells such as SAW resonators[1,2]. In addition, HCT can reduce the required memory size significantly.

Next, let us discuss use of GPU. **Table I** compares catalog specs of CPU and GPU used in this work. Significant difference can be seen in the FP64 (double precision) calculation speed.

Table I. Performance of selected CPU and GPU

	Intel Xeon W-2123	NVIDIA GV100
Cores	4	5,120
Frequency	3.6 GHz	1.132 GHz
FP 64 Performance	0.23 TFLOPS	7.4 TFLOPS
Configured Memory	128 GB DDR4	32 GB HBM2

Fig. 1 compares calculation time for one-time cascading operation as a function of the number n

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of DOFs. It is seen that GPGPU offers significant acceleration, especially when n is large. This is owed to parallel computing using a huge number of cores.

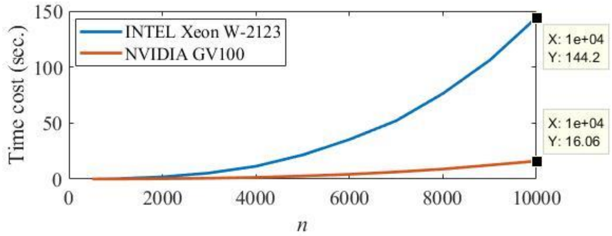


Fig. 1 Time consumption of selected CPU and GPU verse n.

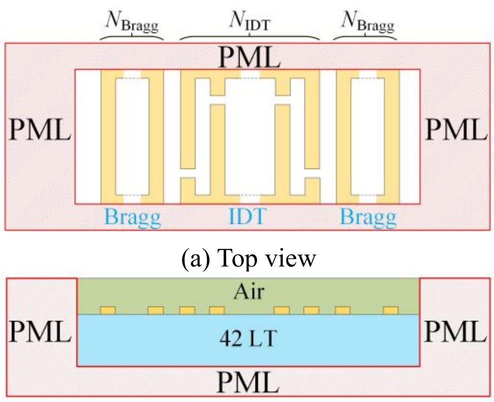
In this GPU calculation, the software package *MAGMA* [4] was applied, and all the calculation could be performed in the GPU. Further increase in n requests data exchange between GPU and main memories due to limited GPU memory, and results in significant deterioration of the calculation speed.

3. 3D FEM simulation

The above discussion implies that GPU based HCT (GPU-HCT) is advantageous for huge models such as 3D FEM. Here we apply the GPU-HCT to the 3D simulation of SAW resonators on 42-LT.

The calculation is performed in following steps[3]. First, several basic models are built in commercial FEM software COMSOL. Then their FEM matrices are extracted and cascaded in MATLAB. Making use of parallel computing toolbox in MATLAB, the processing power of GPGPU can be utilized.

Fig.2 shows the 3D FEM model used in this paper. Perfectly matched layers (PML) are placed in surroundings of the Al electrode region and the bottom of the piezoelectric substrate (42-LT). The IDT period, thickness and aperture are 5.85 μm, 0.3 μm, and 87.75 μm, respectively.



(a) Top view

(b) cross section in middle

Fig.2 Schematic of the final 3D FEM model

First, the numbers of IDT electrodes and Bragg reflectors, N_{IDT} and N_{Bragg}, were set at 5 and 2, respectively, and results obtained by the GPU-based HCT and traditional FEM were compared. Although N_{IDT} and N_{Bragg} are so small, total DOFs are more than 0.9 million, which is almost the upper limit for the traditional FEM.

Table II shows compares required memory size and computation time. GPU-HCT enables to reduce these values significantly even though N_{IDT} and N_{Bragg} are small. Of course, no difference was found between obtained frequency responses.

Table II. Simulation result of FEM model with and without GPU based HCT

	Without HCT	GPU-HCT
Time	745 s	133 s
Maximum used memory	110 GB	2 GB (CPU)+ 28 GB (GPU)

Next, N_{IDT} and N_{Bragg}, were set at 257 and 33, respectively. In the case, the traditional FEM is not applicable due to required memory size. The results are shown in **Fig. 3**. In addition to main and various spurious responses, influence of lateral leakage is clearly seen. Although the number of DOFs was reached to 30 million, the computational time was 153 s for one frequency, which is only 20 s longer than the value shown in Table II. Note that more than 20 min. is necessary if GPGPU is not used.

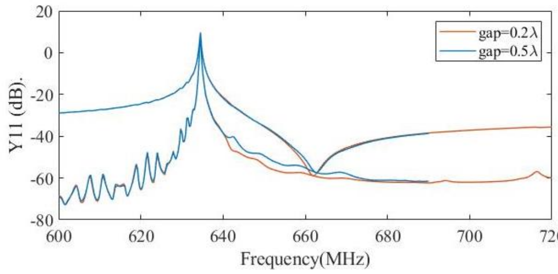


Fig. 3 Simulated Y11 curves of SAW resonator

Although effectiveness of GPU-HCT was demonstrated in this paper, its applicability is limited by the GPU memory size. But rapid advance of GPGPU related technologies will resolve this problem very soon.

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