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The electromagnetic waves propagation in unmagnetized plasma media using parallelized finite-difference time-domain method

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ABSTRACT

The finite-difference time-domain (FDTD) method has been commonly utilized to simulate the electromagnetic (EM) waves propagation in the plasma media. However, the FDTD method may bring about extra run-time on concerning computationally large and complicated EM problems. Fortunately, the FDTD method is easy to parallelize. Besides, GPU has been widely used for parallel computing due to its unique SPMD (Single Program Multiple Data) architecture. In this paper, we represent the parallel Runge-Kutta exponential time differencing scheme FDTD (RKETD) method for the unmagnetized plasma implemented on GPU. The detailed flowchart of parallel RKETD-FDTD method is described. The accuracy and acceleration performance of the proposed parallel RKETD-FDTD method implemented on GPU are substantiated by calculating the reflection and transmission coefficients for one-dimensional unmagnetized plasma slab. The results indicate that the numerical precision of the parallel RKETD-FDTD scheme is consistent with that of the code implemented on CPU. The computation efficiency is greatly improved compared with merely CPU-based serial RKETD-FDTD method. Moreover, the comparisons of the performance of CUDA-based GPU parallel program, Open MP (Open Multi-Processing)-based CPU parallel program, and single-CPU serial program on the same host computer are done. Compared with the serial program, both parallel programs get good results, while GPU-based parallel program gains better result.

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1. Introduction

Since the finite-difference time-domain (FDTD) method was initially delivered to numerically resolve the Maxwell's equations by Yee in 1966 [1]. It has been widely used in the numerical solution of electromagnetics (EMs) problems. The FDTD method has obvious advantages compared to many other numerical methods. It uses the leap frog algorithm—the electric field and the magnetic field in the space domain to perform alternate calculations. So do not need too complicated calculations [2].

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Over the past decades, the FDTD numerical modeling approach has been applied to many aspects, including the modeling of objects in aerospace, biological systems and geometric shapes, the analyzing and designing of complicated microwave circuits, fast time-varying systems and other engineering applications [3]. Plentiful numerical methods related to FDTD formulations used to calculate the EM waves propagation in the dispersive media are addressed, including the recursive convolution (RC) method [4,5], frequency-dependent Z transform method [6,7], direct integration (DI) method [8,9], JE convolution (JEC) method [10], the auxiliary differential equation (ADE) method [11], piecewise linear recursive convolution (PLRC) method [12], piecewise linear current density recursive convolution (PLCDRC) method [13], and Runge-Kutta exponential time differencing (RKETD) method [14]. Simulation of EM waves propagating through the plasma media is a unique and fascinating application built on FDTD formulations for dispersive media. The appearing nonlinear phenomena that are not totally understood can be explicitly refined by numerical simulation. Furthermore, the aforementioned various FDTD scheme for dispersive media can be applied to the plasmas.

Although the FDTD schemes above are well-suited to numerical simulation, the original FDTD method can bring about extra run time owing to computationally large and complicated EM issues. However, FDTD method is naturally a massively parallel algorithm, thus it can benefit a lot from the progresses in parallel computing techniques and effectively reduce the run time. In 2001, an MPI-based parallel FDTD algorithm was proposed [15]. And some physicists used VALU and VAX to speed up parallel FDTD procedures [16]. However, the acceleration of FDTD algorithm was not significant and not easy to implement. OpenMP-based CPU parallel program can be easily achieved in a single host. Researchers have applied it to the FDTD algorithm [17,18], but the acceleration performance has not been improved greatly. And it is difficult to implement parallel computation on multiple hosts. More and more researches begin to focus on the parallelization of FDTD algorithm by GPU to improve computational efficiency. Cannon and Honary utilized OpenCL-based GPU to implement parallel FDTD program and successfully simulated electromagnetic wave propagation in plasma [19]. OpenCL, however, was unfriendly to developers and it did not occupy the mainstream market of general parallel computing. Wang et al, used NVIDIA GPU based CUDA(Compute Unified Device Architecture) parallelization FDTD method and calculated the electromagnetic field propagation in the dielectric in 2016 [20]. In the same year Ryo Imai et al compared the FDTD performance under PML boundary conditions using GPU, MIC and CPU [21]. In 2017, Diener and others compared the CUDA program and MATLAB parallel computing toolbox parallel FDTD method acceleration performance. And numerical simulation results show that CUDA algorithm are more efficient [22]. What's more, FDTD method carried out on multi-GPU clusters has triggered great interest to further accelerate large-scale computations with improved speedup performance [23–26]. However, for complicated medium, dispersive media for instance, the research of parallel FDTD algorithm based on CUDA platform has not been used. So, a parallel FDTD method with higher accuracy and efficiency capable of computing complicated medium is proposed in this paper.

This paper presents a GPU-based parallel RKETD-FDTD method with CUDA for the unmagnetized plasma media to acquire better acceleration performance, compared with merely CPU-based serial RKETD-FDTD method. Numerical simulation of the RKETD-FDTD method for the unmagnetized plasma media is undertaken both on CPU and GPU respectively. The reflection and transmission coefficients through an unmagnetized plasma layer in one dimension are calculated to validate the accuracy of the method. Comparing the CPU-based serial program with the CPU-based parallel program, the calculated acceleration ratio proves the high efficiency of GPU-based parallel RKETD-FDTD method.

This paper is arranged as follows. In Section II, we describe the Maxwell equations for the unmagnetized plasma and derive the FDTD formulation with RKETD numerical scheme. Section III illustrates the implementation of GPU-parallelized RKETD-FDTD method with CUDA. Section IV designs a numerical simulation that is carried out to prove the accuracy and the efficiency of the GPU-based parallel RKETD-FDTD method for unmagnetized plasma.

2. RKETD-FDTD formulation

The famous Maxwell's equations in time domain for the unmagnetized plasma are provided by

$$\nabla \times \boldsymbol{H} = \varepsilon_0 \frac{\partial \boldsymbol{E}}{\partial t} + \boldsymbol{J} \tag{1}$$

$$\nabla \times \boldsymbol{E} = -\mu_0 \frac{\partial \boldsymbol{H}}{\partial t} \tag{2}$$

$$\frac{d\boldsymbol{J}}{dt} + \nu \boldsymbol{J} = \varepsilon_0 \omega_p^2 \boldsymbol{E} \tag{3}$$

where, $\boldsymbol{H}$ is the magnetic intensity, $\boldsymbol{E}$ is the electric field, $\boldsymbol{J}$ is the polarization current density, ν is the electron collision frequency, ω_p is plasma frequency, ε_0 and μ_0 are the permittivity and permeability of free space, respectively. Considering one-dimensional equations, the one-dimensional component of the equations can be written as

$$-\frac{\partial H_y}{\partial z} = \varepsilon_0 \frac{\partial E_x}{\partial t} + J_x \tag{4}$$

$$\frac{\partial E_x}{\partial z} = -\mu_0 \frac{\partial H_y}{\partial t} \tag{5}$$

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