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PARALLEL NUMERICAL MODELLING OF SHORT LASER PULSE COMPRESSION

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Abstract. In this paper we investigate parallel numerical algorithms for solution of the transient stimulated scattering processes. A new symmetrical splitting scheme is proposed and a parallel version is given. The efficiency of the parallel algorithm is investigated for two cases. The first one describes a case when the computation region is constant during the whole time of computations. The second one describes the initial phase of the process, when the computational region increases linearly in time. In order to distribute more evenly jobs between processors a dynamical the grid redistribution algorithm is is used. We also give a proof of one result about optimal static grid distribution in the case of linearly increased problem complexity. The results of computations are presented. They were obtained on different parallel computers and clusters of workstations.

Key words: finite-difference schemes, symmetrical splitting method, parallel algorithms, grid redistribution, nonlinear optics

1. Introduction

Scientific investigations in various fields and different technological applications require laser systems satisfying a number of requirements. They should be able to generate short pulses in various spectral ranges with tunable pulse duration, the generated pulses must be easily synchronized with external events and have a good stability and low jitter [18]. The progress of solid-state lasers with nonlinear-optical phase conjugation and pulse compression will support these objectives for extension of the fields of laser applications [5, 13, 22]. Using different schemes for the stimulated Brillouin scattering (SBS) compressor, it is possible to achieve pulses with durations shorter than 100 ps [4, 5, 6, 13, 22]. Note that a consecutive cascade compression provides a set of precisely synchronized (with the accuracy of several ps) pulses of different wavelengths and pulse durations [13, 19].

In the SBS compression experiments, Fourier-transform-limited laser pulses with Gaussian transversal intensity distribution are commonly used. Therefore, it is of great practical interest to investigate the statistics (energetic, temporal and spectral) of Stokes pulses for different pump pulse parameters and optical schemes of SBS compressor and amplifier. For optimization of SBS compression schemes detailed three-dimensional numerical simulations of the transient backward SBS process for different focusing geometries of phase–modulated pump pulses with different pulse shape and durations starting from spontaneous scattering level are needed.

Performing this type of calculations is also interesting from purely scientific point of view, because a number of works appeared lately [1, 2, 3, 20, 21], presenting some results that contradict the results of our earlier works [7, 8, 16, 17]. It should be pointed out that calculations of the transient stimulated scattering processes, especially in the three-dimensional case, require lengthy computation times. Therefore, without application of the parallel algorithms, the investigation of statistical peculiarities of these processes is practically impossible.

We start from the algorithm developed in [9, 12] for the solution of nonlinear problems with strongly focused beams. It is based on the expansion of the fields of the interacting beams into the series of eigenfunctions of the Laguerre-Gauss type. Such algorithm can be modified into a parallel algorithm easily enough by using data parallelization paradigm [10], see also a paper by Elisseev [15], where a parallel code is obtained using HPF.

This work presents a novel more efficient splitting type scheme and its parallel version. This scheme was tested for a three-dimensional problem of transient stimulated scattering of focused beams. Thus, our goal is to investigate the efficiency of the parallel version of the proposed symmetrical splitting scheme. We study the influence of different nonlinear effects on the accuracy of the obtained numerical solution in order to determine a region of application of the proposed parallel numerical algorithm.

The rest of the paper is organized as follows. In Section 2 we describe a mathematical model of SBS. In Section 3 the new finite difference scheme is presented. A parallel version of this algorithm is presented in Section 4. This section also describes the load balancing problem for the front moving case. Section 5 contains analysis of the obtained numerical results and the last Section 6 draws some conclusions.

2. Mathematical Model

A schema of the numerically modelled SBS compressor is presented in in Fig. 1. Attempts are still being made to investigate this phenomena analytically, but inclusion of the material non-stationarity can be taken into account only numerically.

The presented work gives a new parallel numerical algorithm for solving the system of equations, which describes the nonlinear interaction of laser, Stokes and

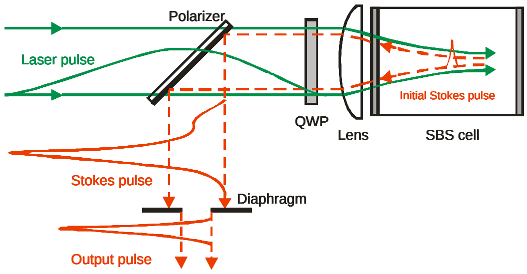

Figure 1. A schema of the SBS compressor.

sound waves. In $0 \le z \le L$, $0 \le r \le R$, $0 \le t \le T$ the following system of equations is given [7, 16]:

$$\begin{cases} \dfrac{\partial u}{\partial t} + \dfrac{\partial u}{\partial z} - i\mu_L A u = i\gamma_L \sigma v + i\omega_L \big(|u|^2 + 2|v|^2\big) u \,, \\ \dfrac{\partial v}{\partial t} - \dfrac{\partial v}{\partial z} - i\mu_S A v = i\gamma_S \sigma^* u + i\omega_S \big(2|u|^2 + |v|^2\big) v \,, \\ i\gamma_0 \Big(\dfrac{\partial^2 \sigma}{\partial t^2} + \gamma_1 \dfrac{\partial \sigma}{\partial t} \Big) + \dfrac{\partial \sigma}{\partial t} + \gamma_2 \sigma = i\gamma_\sigma u v^* + \gamma_f \,, \end{cases} \tag{2.1}$$

here $A = \frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial}{\partial r})$ is the transverse Laplacian, u, v and σ are slowly varying complex amplitudes of laser, the Stokes and the sound waves, respectively. $\gamma_L, \gamma_S, \gamma_\sigma$ are coupling constants, γ_f is the thermal noise parameter, γ_0 and γ_2 are hypersound wave parameters (related to the period and relaxation time). System (2.1) is supplemented with the boundary and initial conditions:

$$\begin{aligned} & u(z=0,r,t) = g_0(r,t), \quad v(z=L,r,t) = g_1(r,t), \quad 0 \le r \le R \,, \\ & r\frac{\partial u}{\partial r}\Big|_{r=0} = 0, \quad r\frac{\partial v}{\partial r}\Big|_{r=0} = 0, \quad 0 \le z \le L, \quad 0 \le t \le T \,, \\ & u(z,R,t) = 0, \quad v(z,R,t) = 0 \,, \\ & u(z,r,0) = 0, \quad v(z,r,0) = 0 \,. \end{aligned}$$

Since for focused beams the diameter of the beam waist in the cuvette is by factor 20-50 and more times smaller than the diameter of input beam, adaptive grids are required in order to solve the problem accurately and effi ciently. Such adaptive strategies have proved to reduce signifi cantly the computational cost for obtaining a numerical solution.

The Schrödinger equation looks very similar to the heat equation, but there are great differences. We note mainly, that the Schrödinger equation does not have a regularizing effect of the contractivity as for the heat equation. Therefore the development of adaptive algorithms for solving the Schrödinger type nonlinear equations requires new techniques. The most popular adaptive schemes are based on application of transformations, which use the properties of solutions of the linear Schrödinger equation. Extensive numerical comparison of different mesh adaptation techniques and transformations is presented in [9]. A new adaptive transformation is proposed in [23], it was also used in [17] for numerical solution of the SBS problem using a splitting finite-difference scheme.

We note that general mesh adaptation techniques are also applied for the Schrödinger problem (see, e.g. [14]). The basis of such procedure is a posteriori error estimate that has to be derived for the obtained discrete solution. Then local error estimators indicate the regions of the computational domain where we have to refine the mesh in order to improve the accuracy of the approximation.

In this work we propose a new symmetrical splitting scheme, in which the diffraction subproblem is solved using the expansion into the Laguerre-Gaussian modes. The accuracy of such an approximation is investigated in [12].

Modelling of nonlinear effects of SBS pulse compression requires to resolve the evolution of all dynamically significant scales of motion. This can be done only via variable mesh densities. The obtained discrete problems often are too large to fit into serial computers, either because of computational demands or memory limitations, or both. Parallel computers and algorithms are the most effective solutions of this problem.

3. Finite Difference Scheme

This section contains a brief description of the numerical algorithm. We introduce the following discrete meshes:

$$\omega_z = \left\{ z_n : \ \ z_n = n\tau, \ \ n = 0, 1, \ldots, N, \ \ \tau = \frac{L}{N} \right\},$$

$$\omega_t = \left\{ t^k : \ \ t^k = k\tau, \ \ k = 0, 1, \ldots, K \right\},$$

$$\omega_r(z) = \left\{ r_j : \ \ r_j = jh, \ \ j = 0, 1, \ldots, J, \ \ h = \frac{R(z)}{J} \right\},$$

here ω_r depends adaptively on the coordinate z and generally this mesh is also nonuniform in r. We use the following notation for discrete functions:

$$U_{nj}^k = U(z_n, r_j, t^k), \quad (z_n, r_j, t^k) \in \omega_z \times \omega_r(z) \times \omega_t \, .$$

We approximate problem (2.1) by the following splitting algorithm.

Symmetrical Splitting Algorithm

for $k = 0, K$
/ First diffraction step */*
for $n = 0, N$

$$U_{n+\frac{1}{2}}^{k+\frac{1}{3}}(r) = \sum_{p=0}^{P} c_p^k(z_n)\, W_p(z_{n+\frac{1}{2}}, r), \quad r \in \omega_r(z_{n+\frac{1}{2}})$$

$$V_{n+\frac{1}{2}}^{k+\frac{1}{3}}(r) = \sum_{p=0}^{P} d_p^k(z_{n+1})\, \overline{W}_p(z_{n+\frac{1}{2}}, r)$$

end for

/ Nonlinear Interaction */*
for $n = 0, N$

$$U_{n+\frac{1}{2}}^{k+\frac{2}{3}}(r) = f_u(U_{n+\frac{1}{2}}^{k+\frac{1}{3}}, V_{n+\frac{1}{2}}^{k+\frac{1}{3}}, \sigma_{n+\frac{1}{2}}^{k}, \delta_{n+\frac{1}{2}}^{k}), \quad r \in \omega_r(z_{n+\frac{1}{2}})$$

$$V_{n+\frac{1}{2}}^{k+\frac{2}{3}}(r) = f_v(U_{n+\frac{1}{2}}^{k+\frac{1}{3}}, V_{n+\frac{1}{2}}^{k+\frac{1}{3}}, \sigma_{n+\frac{1}{2}}^{k}, \delta_{n+\frac{1}{2}}^{k})$$

$$\sigma_{n+\frac{1}{2}}^{k+1}(r) = f_\sigma(U_{n+\frac{1}{2}}^{k+\frac{1}{3}}, V_{n+\frac{1}{2}}^{k+\frac{1}{3}}, \sigma_{n+\frac{1}{2}}^{k}, \delta_{n+\frac{1}{2}}^{k})$$

$$\delta_{n+\frac{1}{2}}^{k+1}(r) = f_\delta(U_{n+\frac{1}{2}}^{k+\frac{1}{3}}, V_{n+\frac{1}{2}}^{k+\frac{1}{3}}, \sigma_{n+\frac{1}{2}}^{k}, \delta_{n+\frac{1}{2}}^{k})$$

end for

/ Second diffraction step */*
for $n = 0, N$

$$c_p^{k+1}(z_{n+1}) = \big(U_{n+\frac{1}{2}}^{k+\frac{2}{3}},\, W_p(z_{n+\frac{1}{2}})\big),$$

$$d_p^{k+1}(z_n) = \big(V_{n+\frac{1}{2}}^{k+\frac{2}{3}},\, \overline{W}_p(z_{n+\frac{1}{2}})\big),$$

$$U_{n+1}^{k+1}(r) = \sum_{p=0}^{P} c_p^{k+1}(z_{n+1})\, W_p(z_{n+1}, r), \quad r \in \omega_r(z_{n+1})$$

$$V_n^{k+1}(r) = \sum_{p=0}^{P} d_p^{k+1}(z_n)\, \overline{W}_p(z_n, r), \quad r \in \omega_r(z_n)$$

end for
end for

The analysis of the algorithm complexity

1 step: Diffraction.

In this step the equations of wave propagation and diffraction are solved in the element $[z_n, z_{n+\frac{1}{2}}]$. The total complexity of this step is $\mathcal{O}(JP)$ operations.

2 step: Nonlinear Interaction.

Using predictor–corrector numerical integration scheme we solve a system of ODEs describing the nonlinear interaction of laser, the Stokes and the sound beams. The complexity of this step is $\mathcal{O}(J)$ operations.

3 step: Diffraction.

We complete the diffraction step, i.e. the laser and Stokes waves again propagate in the second part of the element. The complexity of this step is $\mathcal{O}(JP)$ operations.

Thus the total complexity of the splitting numerical algorithm is $\mathcal{O}(NJP)$ operations.

Due to symmetrical splitting algorithm the accuracy of the finite difference scheme is $\mathcal{O}(h^2 + (\tau^4 + P^{-\alpha})/h)$, where α depends on the smoothness of the exact solution (see, [12]). We note that the error can accumulate linearly with respect to N, thus in order to reduce the global error we need to change also τ and P. This phenomena is investigated in detail in [12].

4. Parallel Algorithm

We use an one–dimensional mesh of virtual p processors. The finite difference grid ω_z is partitioned in p blocks, which are distributed among processors (see Fig. 2).

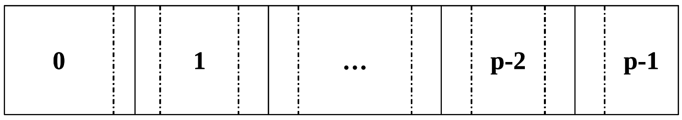

Figure 2. 1D block data distribution.

It follows from the proposed numerical algorithm, that each processor needs to exchange information (i.e., coefficients c_j and d_j) corresponding to the boundary points of its local domain. It is important to note, that communication is done only between neighbour processors. After the communication step each processor has all required information. Now all computations can be performed efficiently in parallel and the results are also stored locally on each processor.

4.1. The analysis of algorithm complexity

First we estimate the parallel execution time of the proposed algorithm during realization of one time step. The discrete problem size can be expressed as follows

$$W = JN(C_1 P + C_2)\,.$$

The communication step on most network architectures can be done in time $T_{comm} = \alpha + \beta P$. Thus the parallel execution time T_p on p processors is given by

$$T_p = \frac{JN}{p}(C_1 P + C_2) + \alpha + \beta P\,.$$

The additional cost of parallel algorithm can be expressed as follows

$$T_0(W, p) = pT_p - W\,.$$

We solve the equation

$$W = eT_0(W, p), \quad e = \frac{E_p}{1 - E_p}, \quad E_p = \frac{W}{W + T_0(W, p)}\,,$$

where E_p is a selected efficiency of the parallel algorithm. Since $p \le N$, and $J = \mathcal{O}(N)$, we get that the proposed parallel algorithm is highly scalable.

The code was implemented using MPI library and performed on IBM SP4 computer. In Table 1 we present speed-up $S_p = \frac{W}{T_p}$ and efficiency $E_p = \frac{S_p}{p}$ data obtained for two discrete problems of different sizes:

a) $N = 201, \quad J = 101, \quad P = 15$ (denoted by S_{1p} in Table 1),

b) $N = 301, \quad J = 151, \quad P = 45$ (denoted by S_{2p} in Table 1).

Table 1. The speed-up and efficiency of the parallel algorithm.

p	S_{1p}	E_{1p}	S_{2p}	E_{2p}
2	1.971	0.986	1.968	0.984
4	3.934	0.984	3.904	0.976
8	7.591	0.949	7.692	0.962
16	14.67	0.917	15.20	0.950
32	24.94	0.780	27.89	0.872

These results fully confirm our theoretical predictions.

4.2. Front moving case

If the boundary condition for the Stokes wave is equal to zero, then during initial transition time $0 \le t^k \le L$ the domain involved in computations enlarges dynamically

$$\omega_z(t^k) = \left\{ z_n : \quad 0 \le z_n \le t^k \right\}$$

and the problem size at the k-th time step is given by $kJ(C_1P + C_2)$ instead of $NJ(C_1P + C_2)$. Then the static mesh partitioning among processors using a block distribution scheme is not optimal. It is shown in [11] that the speed-up of the parallel algorithm is equal to $S_p \approx \frac{p}{2}$, even when the communication costs are not taken into account.

As it was stated in [11] the computation costs can be reduced if we decompose the grid not uniformly. It was proposed to divide the grid into $p + 1$ parts and assign the last two subdomains to the last processor. A simple analysis proved that this heuristic gives optimal static block distributions for $p \le 3$. In the case of $p \ge 4$ the efficiency of the proposed heuristic was investigated numerically.

Now we will give a proof of this statement. In fact, we will show that the first $p - 1$ processors should get equal numbers of grid points D_0 if computations are done at least till time moments $t \ge pD_0$. Here we have assumed that the front moves one grid point per time step.

Theorem 1. *Let consider the static block data distribution, when the grid is divided into $p + 1$ parts and the last processor obtains the last two subdomains. Such distribution scheme is optimal among static block distributions.*

Proof. The proof is based on induction. It is sufficient to consider the following grid distribution:

- the first $(p-2)$ processors obtain D_0 grid points;
- the $(p-1)$th processor gets D_1 grid points;
- the pth processor gets D_2 grid points.

These subproblems satisfy the following relations:

$$M + D_2 = N, \quad (p-2)D_0 + D_1 = M\,. \tag{4.1}$$

Next we compute the complexity of the computational problem. The solution of the problem till $T_1 = D_0$ requires

$$W_1 = \sum_{j=1}^{D_0} j = \frac{D_0(D_0+1)}{2}$$

basic operations. The complexity of the problem for $D_0 + 1 \le t \le M - D_1 + D_0$ is

$$W_2 = \sum_{j=D_0+1}^{M-D_1+D_0} D_0 = D_0(M - D_1)$$

basic operations. The last part of the problem till $t = M$ requires

$$W_3 = \sum_{j=M-D_1+D_0+1}^{M} (j - M + D_1)$$

operations. The total number of operations is given by

$$W = W_1 + W_2 + W_3 = \frac{1}{2}\big(D_1^2 + D_1 - 2D_0D_1 + 2D_0M\big)\ .$$

Now we can find the optimal grid distribution among $(p-1)$ processors, when the problem is solved only till $t = M$. Optimality in this case means that we consider only two free parameters, i.e. D_0 and D_1. By using (4.1) we get

$$\frac{\partial S}{\partial D_0} := (p-2)\big(pD_0 - M - 0.5\big) = 0\,,$$
$$D_0 = \frac{M}{p} + \frac{1}{2p}, \quad D_1 = M - (p-2)D_0 = \frac{2M}{p} - \frac{p-2}{2p}\,.$$

Thus we confirm the result, that the $(p-1)$th processor should get the two last subproblems.

Now let consider the situation, when we still continue computations for $M + 1 \le t \le M + K$. Then we obtain the following estimate of the algorithm complexity:

$$\tilde{W} = W + \sum_{j=M+1}^{M+K} D_1 = W + K\big(M - (p-2)D_0\big)$$

and from the optimality equation it follows that $D_0 = \frac{M+K}{p} + \frac{1}{2p}$. It is easy to find K such, that $D_1(K) = D_0(K)$:

$$\frac{M+K}{p} = \frac{M}{p-1} \quad \Rightarrow \quad K = \frac{M}{p-1} \, .$$

Thus we have proved, that for any number of processors p, the first processors should get subproblems of the size $\frac{M}{p-1}$ and only the last processor gets a subproblem of the size $\frac{2M}{p-1}$. Again, if the computations are continued for $t > N$, then the optimal grid distribution converges to the static block distribution scheme. ■

Dynamic data redistribution

In general, if we distribute the grid using the static block distribution scheme, then the parallel execution time T_p on p processors is given by

$$T_p = \frac{N}{p} J\Big(N - \frac{N}{2p} + \frac{1}{2}\Big)(C_1 P + C_2) + \frac{p-1}{p} N(\alpha + \beta P) \, .$$

The following *data redistribution* algorithm is analyzed theoretically in [11]:

- Initial N_s points of the mesh ω_z are partitioned statically among processors using a block distribution scheme.
- Starting from the time moment $t^k = N_s \tau$ after K_s steps of the algorithm data is redistributed among processors in order to preserve a load balancing.

The algorithm for determination of N_s, K_s is given in [11].

This algorithm introduces additional communication costs, but they are compensated by improved load balancing and therefore a total efficiency of the parallel algorithm is increased. Computational experiments are performed on IBM SP4 computer at CINECA. In Table 2 we present speed-ups $S_p = \frac{W}{T_p}$ of the parallel algorithm for different values of redistribution starting point N_s and the same remaining discrete parameters $N = 400, P = 200, K = 400$.

Table 2. Speed-up of the parallel algorithm with data redistribution.

p	$N_s = 400$	$N_s = 200$	$N_s = 100$	$N_s = p$
2	1.332	1.750	1.910	1.966
4	2.270	3.292	3.707	3.816
8	4.143	5.928	7.021	7.265
16	7.676	11.238	12.826	13.248

As predicted by theoretical analysis the adaptive redistribution algorithm increases essentially the efficiency of the parallel discrete algorithm even for fixed size problems.

5. Numerical Results

These numerical experiments were performed on VGTU cluster of 10 SMP PCs. Each PC contains two 1.4 GHz Pentium III processors. All nodes run Linux. In order to estimate the computational power of this cluster we solved the problem with the following parameters: $N = 1200,\ J = 1200,\ P = 100,\ K = 4200$.

Table 3. Execution time, speed–up and efficiency of the parallel algorithm.

p	T_p	S_p	E_p
1	141029	1.0	1.0
8	17751	7.95	0.99
10	14231	9.91	0.99
20	7166	19.68	0.98

In Table 3 we present execution time T_p, speed-up $S_p = \frac{W}{T_p}$ and efficiency $E_p = \frac{S_p}{p}$. These results fully confirm our theoretical predictions, the parallel algorithm is highly scalable.

6. Conclusions

Parallel algorithms for solution of one important problem of nonlinear optics have been investigated. It has been shown that the parallel domain decomposition algorithm for this problem is highly scalable and it's efficiency is near to one. Detailed modelling of practically interesting cases of pulse compression will be published in physical journals.

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Trumpų lazerio impulsų spūdos skaičiavimo lygiagretusis skaitinis algoritmas

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Nagrinėjamas priverstinės Brijueno sklaidos fokusuotuose pluoštuose uždavinio lygiagretusis skaitinis sprendimo algoritmas. Sukonstruota simetrinio skaidymo baigtinių skirtumų schema, kurios tikslumas yra antrosios eilės. Lygiagretusis algoritmas gautas naudojant duomenų lygiagretumo paradigmą. Detaliai nagrinėjamas dinamiškai didėjančio sudėtingumo uždavinys, modeliuojantis Brijueno sklaidos procesą, kai neužduodama kraštinė sąlyga Stokso bangai. Įrodyta hipotezė apie vieno stacionaraus blokinio duomenų paskirstymo algoritmo optimalumą. Eksperimentiškai ištirtas dinaminis duomenų perskirstymo algoritmas, patvirtintas jo efektyvumas net ir fiksuoto dydžio uždaviniams. Darbe pateikti skaitinio eksperimento, atlikto naudojant VGTU 20 procesorių klasterį, rezultatai. Jie patvirtino gautuosius teorinius rezultatus, išsam¯us fizikiniai rezultatai bus išspausdinti kituose darbuose.