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Penetration of Laser Light Through Biological Materials – Discrete Models of Reflection, Absorption and Scattering

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Abstract: In this paper discrete models of absorption (DiMaLL), reflection (DiMoReLL) and scattering (DiMoScaLL) of laser light by biological materials are described. Individual models are integrated into a complex model – DiMoRAS. All the models are realised by finite automates (homogeneous structures).

Keywords: Laser methods in biology and medicine, discrete modeling.

1. Introduction

The characteristic attributes of biological systems are finality of their parameters and discretion (discontinuity). Discretion is used in the time and spatial approach of their modelling. On the one hand it is assumed that the corresponding area of space is represented by discrete three-dimensional elements – by finite automates; on the other hand development of the system proceeds in discrete time periods. Biological surroundings are characteristic by absorption, reflection, scattering, refraction and diffusion of light beams [1–9].

Use of finite automata and their structural set-up enables, in general, to bring two factors into mathematical model of a real biological system at the same time. These two factors – space and time – are very important (if not crucial) in case of live systems. By modeling through finite automata a micro- and macro-approach is used. From the macro-approach view we are interested in the way how an automate behaves in time in connection with input and output information and formulation of automates (its transition functions). In the micro-approach a structure of system from finite automates is formulated – a structural finite automate, its functioning, interconnection and mutual affection of its parts. Homogeneous structure is one of the most important generalization of structural finite automata and is characterized by format of status vector (format of status space), number of possible states of one finite automaton (i,j,k), definition of sequenced surroundings of primary element, one finite automaton (i,j,k) and its elementary transition function. Behavior of a homogeneous structure (sequence of status homogeneous structure in consecutive time periods of discrete time) is through the status function and the basic transition function [8–10].

The functional relations (spot models) are used for definition of concrete functions and numerical calculation of values [11–12].

2. Materials and Methods

All the models are realized by finite automata (cellular automata, homogeneous structures). Finite automata comply with basic three-dimensional (cubic) elements of bounded area of biological material. Each of the three-dimensional elements is defined by trinity of integer coordinates (*i, j, k*). For each of the elements (*i, j, k*) a status vector $D_{i,j,k} = D(i,j,k)$ is defined in discrete time *t*. The status vector $D_{i,j,k}$ contains four basic components that are generally vectorial elements of three-dimensional matrices defining intensity of laser light (matrix **I**), standardized values of reflection (matrix **R**), absorption (matrix **P** and matrix **A**) and scattering (matrix **S**) of laser light in individual three-dimensional elements. Spot functional models of reflection, absorption and scattering of laser light, characteristics of which comply with concrete biological materials, are used for definition of the corresponding values. Transition rules of the status vector are expressed by Boolean functions.

3. Results

The defined area of biologic material is represented by a set of ranked three-dimensional spatial elements (i, j, k). Surround $O_{i,j,k} = O(x_i, y_j, z_k)$ of this element (i, j, k) is created, besides itself, also by its neighbouring elements: {(i-1, j, k), (i+1, j, k), (i, j-1, k), (i, j+1, k), (i, j, k-1), (i, j, k+1)}, (see Fig. 1).

3.1. Discrete Model of Absorption of Laser Light DiMALL

For each element (i, j, k) its permeability of laser light is defined, which is determined qualitatively. Thereby a permeability matrix is defined (for each wave-length) **P** = (P(i,j,k)), while P(i,j,k)   {00, 01, 10, 11}, while

code 00 represents the zero permeability;
code 01 represents the low permeability;
code 10 represents the partial permeability and
code 11 represents the strong permeability.

Therein after values of radiation intensity I_1 to I_6 (see Fig. 2) are defined for each element (i, j, k). Thereby the following relations are valid:

$I_1(i, j, k) = I_3(i, j+1, k);$
$I_2(i, j, k) = I_4(i+1, j, k);$
$I_3(i, j, k) = I_1(i, j-1, k);$
$I_4(i, j, k) = I_2(i-1, j, k);$
$I_5(i, j, k) = R(i, j, k+1),$

and $I_6(i, j, k) = I(i, j, k)$ is the intensity of incoming laser light.

Values of laser light absorption in direction z for all the elements (i, j, k) are defined by matrix $\mathbf{A} = (A^t_z(i, j, k))$, while

$A^t_z(i, j, k) = I^t(i, j, k) - I^t(i, j, k+1) + 1/5\ \underline{I}^t(i, j, k)$, where $\underline{I}^t(i, j, k) = \sum_{n=1}^{4} I^t_n(i, j, k)$

and index *t* represents the period of discrete time.

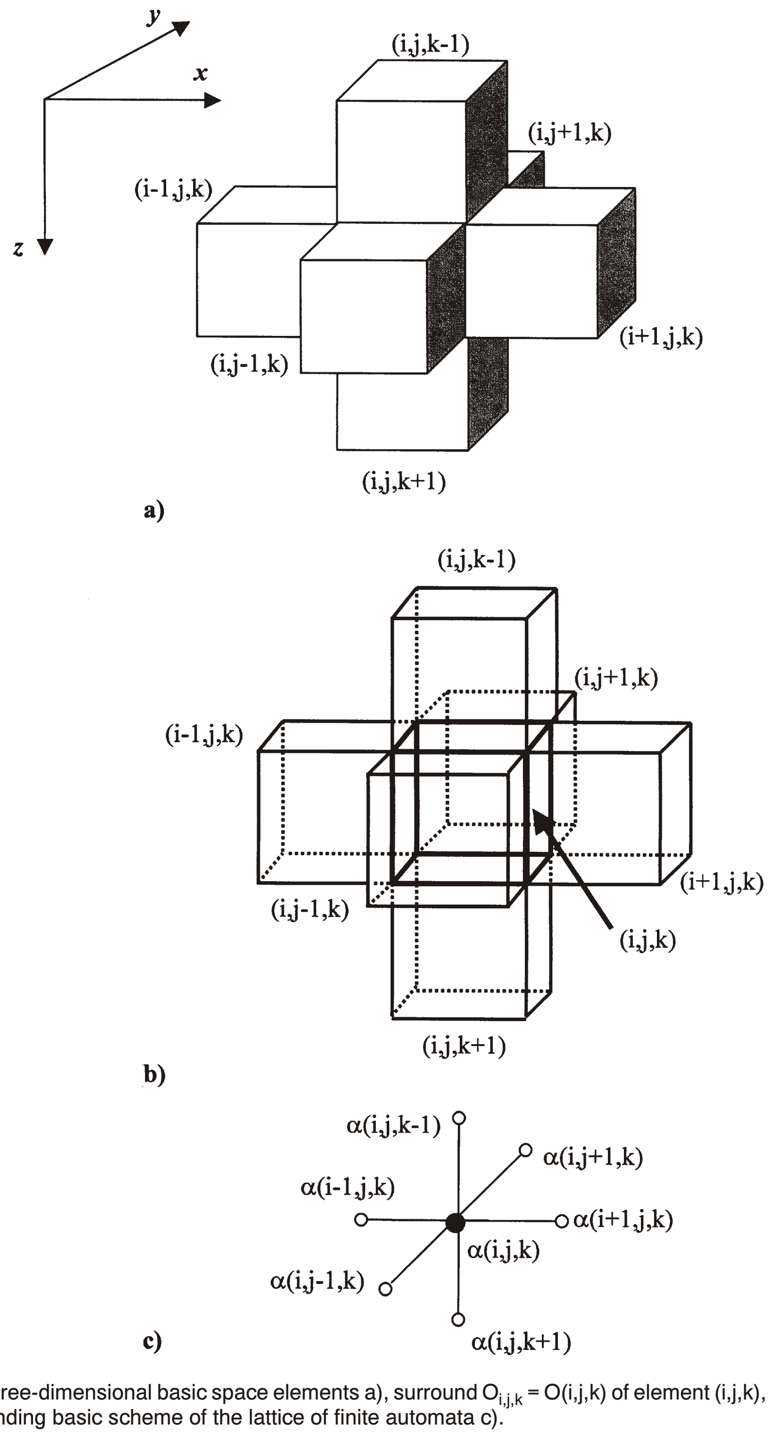

Fig. 1. Three-dimensional basic space elements a), surround $O_{i,j,k}$ = O(i,j,k) of element (i,j,k), b) and the corresponding basic scheme of the lattice of finite automata c).

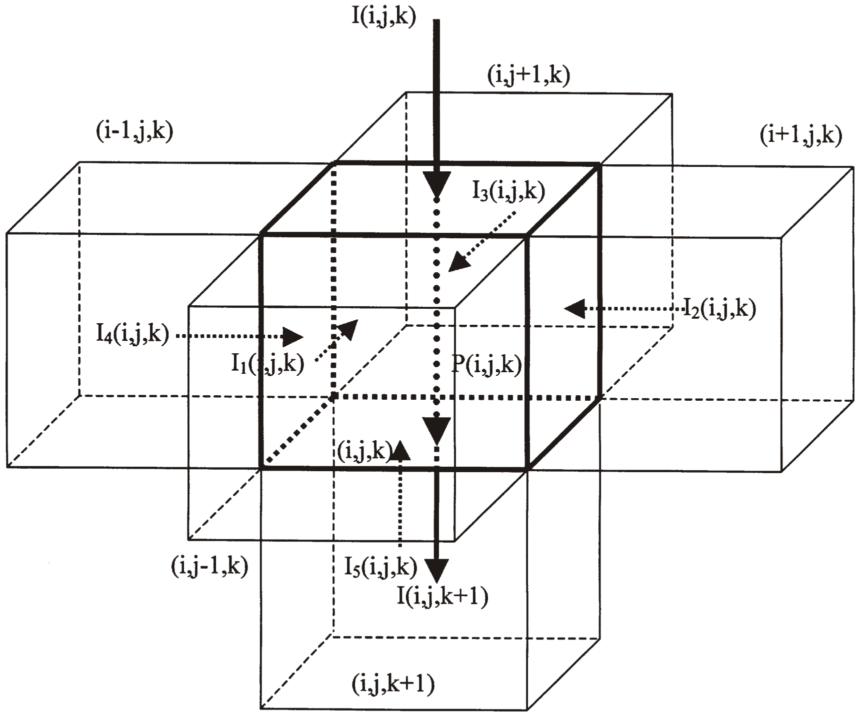

Fig. 2. The basic (local) scheme of discrete model of absorption of laser light DiMALL (matrix **P** = (P(i,j,k)) and matrix **I** = (I(i,j,k))).

The elements of matrix **A** = (A(i,j,k)) are constructed by the use of corresponding elements of matrix **P** = (P(i,j,k)).

There is a natural assumption that $I^t(i, j, k) >> \underline{I}^t(i, j, k)$, for $t = 0$ (t   h).
Whereas the assumed direction of laser light is without a harm on generality in direction of axis z, it is possible to omit index z (values $A_x^t(i, j, k)$ or $A_y^t(i, j, k)$ could be defined analogically). For laser light intensity two boundary values – h_0 and h_1 ($2h_0 < h_1$), are defined. Laser light intensity is coded by binary couples 00, 01, 10, 11, while

00 is the code for $I^t(i, j, k) = 0$;
01 is the code for $0 < I^t(i, j, k)$ h_0;
10 is the code for $h_0 < I^t(i, j, k)$ h_1;
11 is the code for $I^t(i, j, k) > h_1$.

In case 01 laser light could go through the next element only if $\underline{I}^t > 5h_1$. In case 10 laser light could go through the next elements eventually through more following elements when $\underline{I}^t > 5h_0$. In case 11 the laser light could go through more following elements.

By individual levels of permeability laser light goes through the next element
for 01 (low permeability): if $\underline{I}^t > 5h_1$ or for $I^t(i, j, k)$ code 11 is valid;
for 10 (partial permeability): if $\underline{I}^t > 5h_0$ or for $I^t(i, j, k)$ code 10 or 11 is valid.

We assume for simplification that laser light passes through one element during one unit of discrete time. Then we can define $t = z$ (see Fig. 3).

Transition functions for $I^t(i, j, k) \quad I^t(i, j, k+1)$ have shape

$$(|P^t(i,j,k)|, |I^t(i, j, k)|, |\underline{I}^t(i,j,k)|) \quad |I^t(i, j, k+1)|,$$

where $|P^t(i,j,k)|$ – code of $P^t(i,j,k) = x_1x_2$; $|I^t(i, j, k)|$ – code of $I^t(i, j, k) = x_3x_4$; $|\underline{I}^t(i,j,k)|$ – code of $\underline{I}^t(i,j,k) = x_5x_6$; $|I^t(i, j, k+1)|$ – code of $I^t(i, j, k+1) = f_1f_2$.

and by the use of Boolean variables

$$(x_1x_2\ x_3x_4\ x_5x_6) \quad (f_1f_2),$$

where $f_1 = f_1(x_1, x_2, x_3, x_4, x_5, x_6)$ and $f_2 = f_2(x_1, x_2, x_3, x_4, x_5, x_6)$.

In the concrete, for absorption in DiMALL model, the Boolean transition functions are determined by the function tables (Table 1) and after partial minimization they have shape

$$f_1(x_1, x_2, x_3, x_4, x_5, x_6) = f_{11}(x_1, x_2, x_3, x_4, x_5, x_6) \quad f_{12}(x_1, x_2, x_3, x_4, x_5, x_6),$$

where

$$f_{11}(x_1, x_2, x_3, x_4, x_5, x_6) =$$
$$= x_1 (x_2 (x_3 \quad x_3x_5) \quad x_2(x_3 (x_4 (x_5 \quad c_5x_6) \quad \bar{x}_4x_5x_6)x5 \quad x_3x_5(x_4 \quad \bar{x}_4x_5)));$$

$$f_{12}(x_1, x_2, x_3, x_4, x_5, x_6) = x_2x_4x_6(x_1\bar{x}_3\bar{x}_5 \quad \bar{x}_1 x_3x_5) \quad (x_1 \bar{x}_2 x_3 \bar{x}_4 x_5 \bar{x}_6),$$

if $I^t(i, j, k) + \underline{I}^t(i,j,k)/5 >> h_1$;

0, in the opposite case;

and

$$f_2(x_1, x_2, x_3, x_4, x_5, x_6) = f_{21}(x_1, x_2, x_3, x_4, x_5, x_6) \quad f_{22}(x_1, x_2, x_3, x_4, x_5, x_6),$$

where

$$f_{21}(x_1, x_2, x_3, x_4, x_5, x_6) = x_1 (x_2 (\bar{x}_3\bar{x}_4x_6 \quad x_4(\bar{x}_5 \quad x_5x_6)) \quad x_3(x_4 \quad \bar{x}_4x_5x_6)$$
$$x_2(x_4(x_3(x_5x_6) \quad x_5x_6) \quad x_3 x_5x_6) \quad x_3x_4x_5x_6)$$
$$x_1x_2(x_3x_4 \quad x_5x_6(x_3x_4 \quad x_3x_4 \quad x_3x_4));$$

$$f_{22}(x_1, x_2, x_3, x_4, x_5, x_6) = x_1 (x_2x_3\bar{x}_4(x_5\bar{x}_6 \quad \bar{x}_5x_6) \quad \bar{x}_2x_5(x_3(x_4\bar{x}_6 \quad \bar{x}_4x_6) \quad \bar{x}_3x_4x_6)),$$

if $I^t(i, j, k) + \underline{I}^t(i, j, k)/5 >> h_1$;

0, in the opposite case.

3.2. Discrete Model of Reflection of Laser Light DiMoReLL

Reflection matrix $\mathbf{R} = (R^t(i,j,k))$ is, in model DiMoReLL, defined anallogically like in the previous model DiMALL. Vectors $R^t(i,j,k) = (R_1^t(i,j,k), R_1^t(i,j,k), R_3^t(i,j,k), R_4^t(i,j,k), R_6^t(i,j,k))$ are its elements defining reflection values for individual neighboring elements of element (i, j, k). Basic (local) scheme is plotted in Fig. 4.

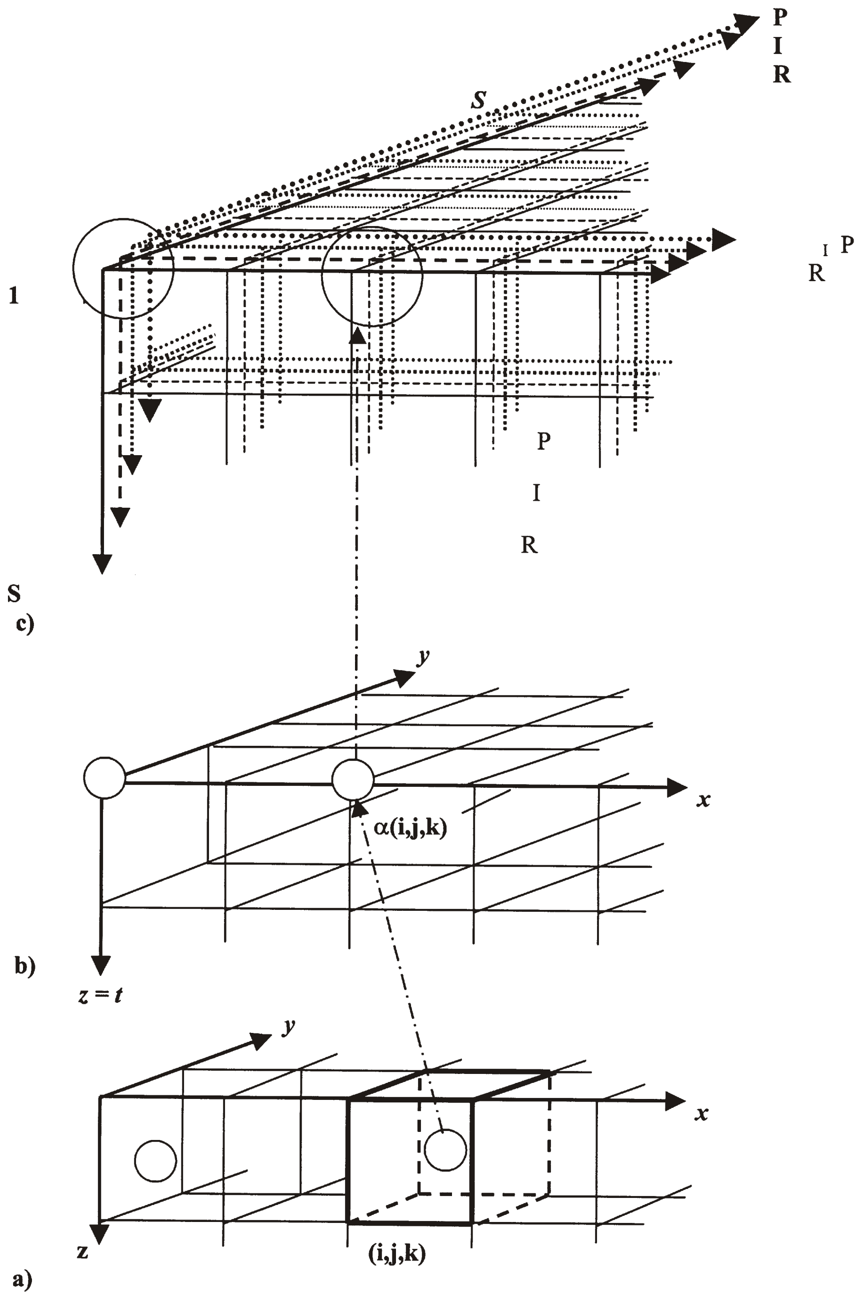

Fig. 3. Three-dimensional basic space element (i,j,k): a) and corresponding automaton (i,j,k) in the lattice of finite automata b). a) shows the distribution of the state vector among four matrices **P** = (P(i,j,k)), **I** = (I(i,j,k)), **R** = (R(i,j,k)) and **S** = (S(i,j,k)).

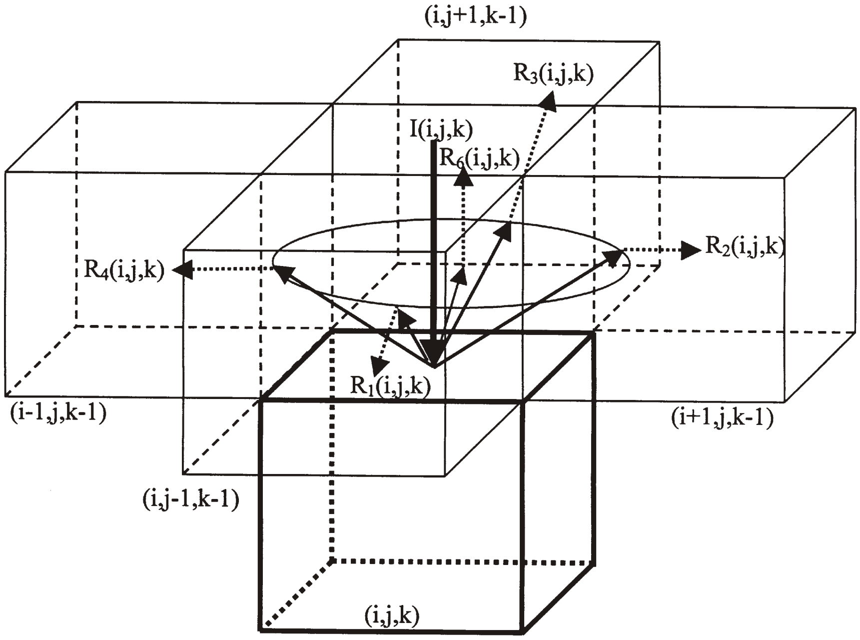

Fig. 4. The basic (local) scheme of discrete model of reflection of laser light DiMoReLL (matrix **R** = (R(i,j,k)).

3.3. Discrete Model of Scattering of Laser Light DiMoScaLL

Scattering matrix **S** = (S^t (i,j,k)) is defined in DiMoScaLL model and its elements are vectors S^t (i,j,k) = (S^t_1(i,j,k), S^t_1(i,j,k), S^t_3(i,j,k), S^t_4(i,j,k), S^t_6(i,j,k)) defining values of scattering for individual neighboring elements of element (i, j, k). Basic (local) scheme is plotted in Fig. 5.

3.4. Complex Discrete Model of Reflection, Absorption and Scattering of Laser Light DiMoRAS

Complex model DiMoRAS is a functional unification of models DiMALL, DiMoReLL and DiMoScaLL. Its basic (local) scheme is plotted in Fig. 6.

4. Discussion

In all the described models known functional relations (spot models) are used for definition of concrete values of individual elements of particular matrices. In these relations directly experimentally measured parameters for the defined biologic materials are used.

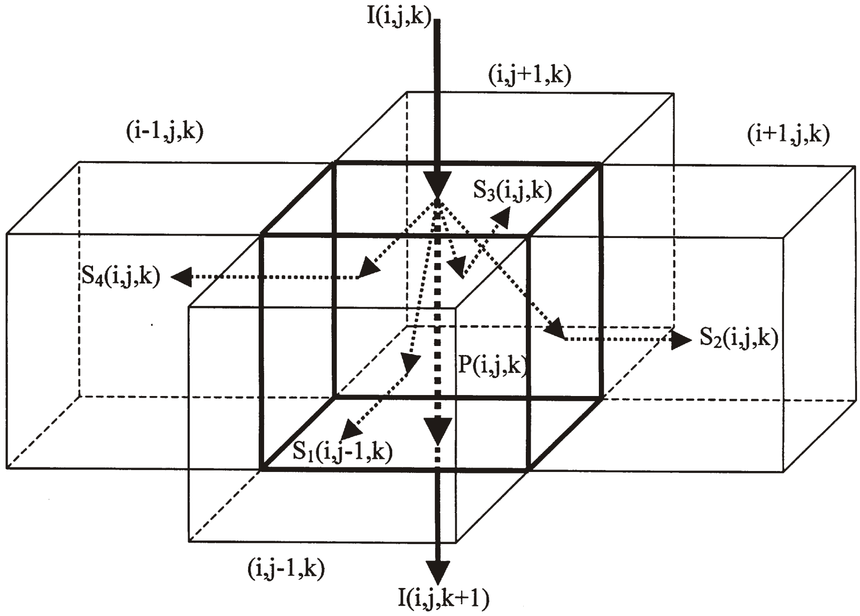

Fig. 5. The basic (local) scheme of discrete model of scattering of laser light DiMoScaLL (matrix **S** = (S(i,j,k)).

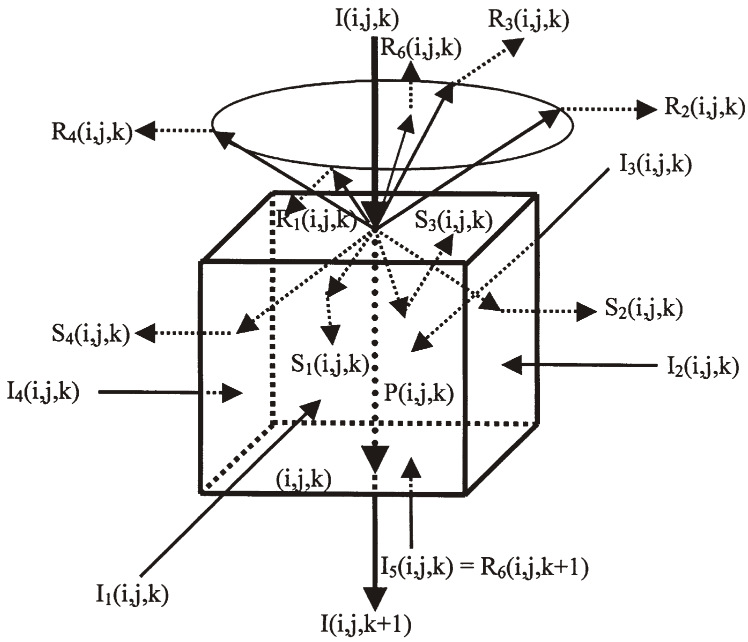

Fig. 6. The basic (local) scheme of complex discrete model of reflection, absorption and scattering of laser light DiMoRAS (matrix **D** is the four of matrices **P**, **I**, **R** and **S** – **D** = (**P**, **I**, **R**, **S**), **D** = ($D_{i,j,k}$), where **P** = (P(i,j,k)), **I** = (I(i,j,k)), **R** = (R(i,j,k)), **S** = (S(i,j,k)) and $D_{i,j,k}$ = D(i,j,k) = (P(i,j,k), I(i,j,k), R(i,j,k), S(i,j,k))).

$$|\underline{I}^t(i,j,k)|$$
$$\Downarrow$$
$$|P^t(i,j,k)|, |I^t(i,j,k)| \Rightarrow |I^t(i,j,k+1)|$$

$\lvert P(i,j,k)\rvert$ $x_1 x_2$	$\lvert I(i,j,k)\rvert$ $x_3 x_4$	x_5 = 0, x_6 = 0	x_5 = 0, x_6 = 1	x_5 = 1, x_6 = 0	x_5 = 1, x_6 = 1 ($\lvert \underline{I}(i,j,k)\rvert$)
0 0	0 0				
	0 1				
	1 0	0 0			
	1 1				
0 1	0 0	00	00	00	01
	0 1	00	00	00	01
	1 0	00	00	00	01
	1 1	01	01	01	01
1 0	0 0	00	00	01	10
	0 1	00	00	10	$\underline{10}$
	1 0	00	01	01	$\underline{10}$
	1 1	00	10	$\underline{10}$	11
1 1	0 0	00	01	10	11
	0 1	01	01	10	11
	1 0	10	$\underline{10}$	$\underline{10}$	11
	1 1	11	11	11	11

Table 1. Tables of transition functions for $I^t(i,j,k)$ $I^t(i,j,k+1)$
(the code functions $f_1 = f_1(x_1, x_2, x_3, x_4, x_5, x_6)$, $f_2 = f_2(x_1, x_2, x_3, x_4, x_5, x_6)$).
$|P^t(i,j,k)|$ – code of $P^t(i,j,k) = x_1x_2$; $|I^t(i,j,k)|$ – code of $I^t(i,j,k) = x_3x_4$;
$|\underline{I}^t(i,j,k)|$ – code of $\underline{I}^t(i,j,k) = x_5x_6$; $|I^t(i,j,k+1)|$ – code of $I^t(i,j,k+1) = f_1f_2$.
$\underline{10}$ = 11, if $I^t(i,j,k) + \underline{I}^t(i,j,k)/5 >> h_1$;
10, in the opposite case.

Acknowledgements

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