Reviews UDK 66.017/.018:620.1/.2
doi: 10.7251/COMEN1701091S

# FORMALISMS, ANALYSIS, RESULTS AND ACCOMPLISHMENTS WITH POPULATION INVERSION OF MATERIALS

*Milesa Ž. Srećković[1], Andrei A. Ionin[2], Aco J. Janićijević[3*], Aleksandar R. Bugarinović[4], Stanko M. Ostojić[3], Milovan M. Janićijević[5], Nada V. Ratković Kovačević[6]*

[1] University of Belgrade, Faculty of Electrical Engineering, Bulevar kralja Aleksandra 73, 11000 Belgrade, Serbia
[2] P. N. Lebedev Physical Institute of the Russian Academy of Sciences, 53 Leninskiy Prospekt, 119991, Moscow, Russia
[3] University of Belgrade, Faculty of Technology and Metallurgy, Karnegijeva 4, 11000 Belgrade, Serbia
[4] Telekom Srpske, 76300 Bijeljina, Republic of Srpska, Bosnia and Herzegovina
[5] Metalac A. D., 32300 Gornji Milanovac, Kneza Aleksandra 212, Serbia
[6] Technical College of Vocational Studies, Požarevac, Nemanjina 2, Serbia

**Abstract**: During six decades of quantum electronics, a vast majority of new types of quantum generators have been developed. Although the principle of population inversion has united different ranges of electromagnetic spectra (and respective quantum generators), the existence of the title *laser without the population inversion*, makes that the exception had confirmed the rule, i. e. that this title deserves to be discussed further. Developing of formalisms describing the operation of quantum generators, by now have produced several approaches, which must have a quantum mechanics base. For the practical reasons, negative coefficient of absorption is acquired using classic electromagnetics as well, however for the population purposes, quantum representation must be entered.

A few levels of formalisms will be set in this paper, linked to quantum generators accenting the optical portion of the spectra. The lowest level descriptions are based on lumped circuits. This could be expanded to equivalents of other physical problems, using program packages developed for the electrical engineering application purposes (Spice, etc.). Schematics are defined at the macro as well as micro equivalent levels (atomic – electronic levels). The kinetic equations with simpler approach will be considered as well as simplified laser equations based on quantum/ semi-quantum approach. The use of Fourier analysis or other appropriate transformations leads to formulating the main five laser equations which serve as the base for various working regimes of quantum generators and amplifiers (free generation regime, $Q$ switch, synchronization, operation with filters, two modes regime, regime with losses, etc.). The Lyapunov stability theorem has to be included here, etc.

For some of the chosen types of quantum generator, analytical modeling will be analyzed as well as the results of program packages developed for the lasers dynamics, regimes and parameters. The systems pumped with electronic beams (relativistic) will be considered and the nuclear physics statements discussed which must be included at the beginning, in order to consider further necessary parts of the condensed – solid state theory and laser techniques, after slowing down towards thermal energies.

Existing program packages provide fast modeling and visualization of laser energy distribution, temperature, modes, etc. in active material with or without the resonator. A modeling will be performed for the specified geometries and a temperature distribution in active material will be captured during operation of a chosen laser system. Different pump geometries will be compared. Contemporary lasers with the shortest existing pulse durations demand new formalisms. Areas of nonlinear optics and quantum electrody-namics, Glauber states and similar, are areas that have to be included. Two main formalisms thermodynamical and quantum mechanical with transition probabilities using perturbation methods and secondary quantization naturally had to be complemented if the Brillouin, Raman, Compton, soliton, fiber and other lasers are included more generally.

**Keywords**: quantum generators, formalisms, dynamics, modeling, laser.

[*] Corresponding author: janicaco@tmf.bg.ac.rs

## 1. INTRODUCTION

Quantum electronics, laser technique, laser electronics and quantum optics are now independent disciplines which have originated from the crossings of several sciences. Along with the theory developed and experimental results, tremendous number of applications exists today concerning directly the quantum generators and amplifiers. From the beginning until today, many theoretical approaches with fundamental, phenomenological or specifically limited dynamical regimes were developed. Nevertheless, all proper approaches have to be traced using contemporary formalisms of quantum mechanics as well as quantum electrodynamics, relativistic effects and nonlinear effects [1−20]. Here, in our paper, several different formalisms connected to generalization as considered in [21] are presented, as well as some specific approaches for defined laser types. The complexity of the tasks such as obtaining the *lasing* effect, thermal distribution connected to active materials, lumped circuits and program packages for designing simulation and fast evaluation will be treated and analyzed here.

## 2. ONE APPROACH TO BASIC *LASING* THEORY

The majority of lasing theories start with forming of the first order differential equations regarding population. These equations for population have the constants of the probability of the transitions or *Einsteins* coefficients and in accordance to spectroscopy formalisms. The equations are formed for the two-, three-, four- or the multi-level systems and in general can be described with

$$\frac{dN_i}{dt} = -N_i\left(\sum_{j=1}^{n}\omega_{ij}^{bz}\delta_{ij} + \sum_{j=1}^{n}W_{ij}\delta_{ij}\right) + \sum_{j=1}^{n}N_j\left(\omega_{ji}^{bz} + W_{ji}\right)\delta_{ij} \quad (1a)$$

$$\sum_{i=1}^{n}N_i = const = N_0 \quad , \qquad (1б)$$

where ($i$ = 1, 2, …, $n$), $\delta$ - Kronecker symbol; $N_i$ − populations, $\omega_{ij}^{bz}$, $W_{ij}$, transition probabilities (with and without radiation), and $N_0$ - total population of levels concerned.

Conditions for population inversion evaluation are formulated by the system presented. Now, we will restart using other approach to formulate dynamical regime in the systems of microparticles.

The equations of the electromagnetic field and the material equation serve to obtain basic approaches for laser amplifiers and generators. The semiclassical theory of lasers is based on Maxwell equations for the electromagnetic field and on the Schrödinger equations for the active material. This model provides an explanation of basic experimental results. The formalism of quantum electrodynamics leads to more complex equations and solutions. The simplest model is based on equations of dynamic equilibrium, which ignore phase relationships in the description of the electromagnetic field. These results can be initial and serve as well for more stringent design and solution.

In a semiclassical approach, the EM field is considered to be a source of macroscopic polarization of the medium $P(z, t)$ and start should be made from Maxwell equations:

$$rotrotE + \mu_0\sigma\frac{\partial E}{\partial t} + \mu_0\varepsilon_0\frac{\partial^2 E}{\partial t^2} = -\mu_0\frac{\partial^2 P}{\partial t^2}$$
(2)

For the majority of lasers, the beam propagates predominantly in the one direction, leading to:

$$\frac{\partial^2 E}{\partial z^2} + \mu_0\sigma\frac{\partial E}{\partial t} - \mu_0\varepsilon_0\frac{\partial^2 E}{\partial t^2} = \mu_0\frac{\partial^2 P}{\partial t^2} \qquad (3)$$

The electric field of induced oscillations, denoted $E_n$, is decoupled into its eigenvalues – the resonator modes (expansion into series of functions):

$$E_n = U_n(z)\exp(i\omega_n t) \quad ,$$
$$E_n(z,t) = \sum_n A_n(t)U_n(z) \quad , \qquad (4)$$
$$U_n(z) = sin\frac{\pi nz}{L} \quad ,$$

which represents the distribution of the EM field along the optical axis with the orthogonal properties of its eigenvalue functions ($A_n$ - amplitude).

$$\frac{d^2A_n}{dt^2} + \frac{\omega}{Q_n}\frac{dA_n}{dt} + \omega_n^2A_n = -\frac{4\pi}{\varepsilon_0}\frac{d^2P_n(t)}{dt^2} \quad , \qquad (5)$$

with the quality factor for the mode $n$, $Q_n = \frac{\varepsilon_0\omega_n}{\sigma}$ ,

$$P_n(t) = \frac{2}{L}\int_0^L P(z,t)U_n(z)dz \quad , \qquad (6)$$

where $P(z, t)$ is a spatial Fourier component [22].

In case the polarization is related to a quasi-monochromatic wave having the frequency $\omega$ near $\omega_n$, a simpler equation is obtained:

$$\frac{d^2A_n}{dt^2} + \frac{\omega}{Q_n}\frac{dA_n}{dt} + \omega_n^2A_n = -\frac{4\pi\omega^2}{\varepsilon_0}P_n(t) \quad . \qquad (7)$$

The material equations are based on inducing the dipole moment, $d$:

$$d = \kappa E(t) \ , \tag{8}$$

where $\kappa$ is the atomic polarization, and the definitions of the macroscopic polarization vector with the introduction of the radius (instead of the vector $z$), the location of the preferred direction of expansion is:

$$\vec{P}(\vec{r},t) = \sum_{m} \vec{d}(\vec{r},t) \ . \tag{9}$$

When material has only two nondegenerated energy levels, the interaction Hamiltonian operator, $\hat{H}_0$, has eigenvalues $W_1$ and $W_2$, hence the matrix form is:

$$\hat{H}_0 = \begin{Vmatrix} W_1 & 0 \\ 0 & W_2 \end{Vmatrix} \ . \tag{10}$$

The interaction of an atom with an external electromagnetic field is described by the interaction Hamiltonian, $\hat{H}'$, whose matrix elements are determined by the matrix elements of the operator of the electric dipole moment, $d$:

$$\hat{H}' = \begin{Vmatrix} 0 & -d_{12}E \\ -d_{21}E & 0 \end{Vmatrix} \ . \tag{11}$$

Formalism also includes density matrix, which, for atoms, has two levels:

$$\hat{\rho} = \begin{Vmatrix} \rho_{11} & \rho_{12} \\ \rho_{21} & \rho_{22} \end{Vmatrix} \ . \tag{12}$$

After adequate substitutions and formalisms are being made and prescribed procedures are carried out, five equations are obtained, which are in the macroscopic notation for the quantum generator describing polarization, population inversion $N$, field $E$ and the times of relaxation:

$$\frac{\partial^2 P}{\partial t^2} + \frac{2}{T_2}\frac{\partial P}{\partial t} + \left(\omega_{21}^2 + \frac{1}{T_2^2}\right)P = -\frac{2\omega_{21}|d|^2}{\hbar}EN \, , \tag{13}$$

$$\frac{\partial N}{\partial t} + \frac{1}{T_1}(N - N_0) = -\frac{2E}{\hbar\omega_{21}}\left[\frac{\partial P}{\partial t} + \frac{P}{T_2}\right] \ , \tag{14}$$

To the two equations given above, (13) and (14), three equations, namely (4), (5) and (6), should be added too, where:

$$N = N_2 - N_1 \ , \ N_0 = N_2^0 - N_1^0 \ . \tag{15}$$

Further modeling requires solutions for stationary (steady state) and non-stationary amplifications, non-stationary generation, progressive amplifiers and various operating modes: two-mode generator with homogeneous broadened linewidth, transient regime, generators with non-stationary parameters, with $Q$-factor modulation, non-linear losses and generators with non-linear absorption filters. For the most of the practical applications, the generators are in the CW (*continuous wave*) and pulse mode (in short and long pulse regimes). Ultra-fast pulses are far from the initial pulses of the free generation regime (spikes) or the first Q-switches (these have reached the atto- and zepto-sec). *Lasing* process modeling is obtained by using an appropriate equation set (five laser equations mentioned before). After appropriate equation set is formed, adequate substituting should be made with respect to the specific *lasing* regime.

**a) For stationary amplification**: $E_{sp} = 0{,}5E(z)\exp(i(\omega t + kz)) + kk$ ($kk$ – complex conjugate term), and analogously modeled $P_{sp}$, $N = N(z)$, followed by a system of three partial equations with complex variables, where after appropriate formalisms and grouping of variables is done, the characteristic partial differential equation of the first order is obtained:

$$\frac{\partial J(z)}{\partial z} = \left[\frac{\beta_0}{1 + \alpha J} - \gamma\right]J \ , \tag{16}$$

where: $J = \frac{n\varepsilon_0 c|E(z)|^2}{2}$ is intensity of progressive wave, $\alpha = \frac{n\varepsilon_0 c\hbar^2}{2T_1T_2|d|^2}$ – saturation parameter, $\beta_0 = \frac{\omega_{21}T_2|d|^2 N(z)}{\hbar\varepsilon_0 cn}$ – unsaturated gain coefficient, and $\gamma = \frac{\mu_0\sigma c}{n}$ – losses.

The kinetic equation (1.16) includes radiation losses, characterizes the energy transfer rate in the material with the progressive wave and does not contain information regarding the fields phase.

**b) In the modeling of nonstationary amplification** $P_{np} = 0{,}5P(z,t)\exp(i(\omega t + kz)) + kk$, $E \rightarrow E_{np}$ is analogously introduced and $N = N(z)$. More complex equation is produced and should be solved:

$$\frac{\partial J(z,t)}{\partial z} + \frac{n}{c}\frac{\partial J(z,t)}{\partial t} = \left[\frac{\beta_0}{1 + \alpha J} - \gamma\right]J \ . \tag{17}$$

**c) A non-stationary generation** assumes dependency

$$P_{ng} = 0{,}5P(t)\exp(i(\omega t)) + kk \ , \tag{18}$$

$E_{ng} = 0{,}5E(t)\exp(i(\omega t)) + kk$, where $P$ and $E$ are slowly changing in time. It is assumed that $\omega \gg \frac{1}{T_2}$, $\omega \gg \frac{1}{T_P}$, $\omega = \omega_{21} = \omega_p$, $\frac{\partial P}{\partial t} \ll \omega P$, $\frac{\partial E}{\partial t} \ll \omega E$, $T_p = \frac{Q}{\omega_p}$ is the decay time in the resonator, $\omega_p$ is a resonant frequency. Again, by grouping of the parameters, simplified partial rate equations are obtained. Similarly, the same is performed when designing progressive wave amplifiers as well as for the maser; while the characteristics of the material are contained in the groups of populations and adequate constants and parameters.

**Two-mode generator with homogeneously broaden line:** Initially the model is formed, which includes variations of a single mode case with coupling of the two modes of intensities $J_1$ and $J_2$ and respective parameters $\alpha_i$ and $\beta_i$ (following the modeling of a single mode and analogous to the equation 16) and the coupling parameters $\theta_{ij}$

$$\frac{dJ_1}{dt} = J_1\left(\beta_1 - \alpha_1 J_1 - \theta_{12} J_2\right) \; , \tag{19}$$

$$\frac{dJ_2}{dt} = J_2\left(\beta_2 - \alpha_2 J_2 - \theta_{21} J_1\right) \; . \tag{20}$$

The solution allows to consider in more detail cases of strong and weak coupling − Figure 1; $N = N(z)$ is now obtained for solving, and the dependence on mirror reflection and the output power is further defined.

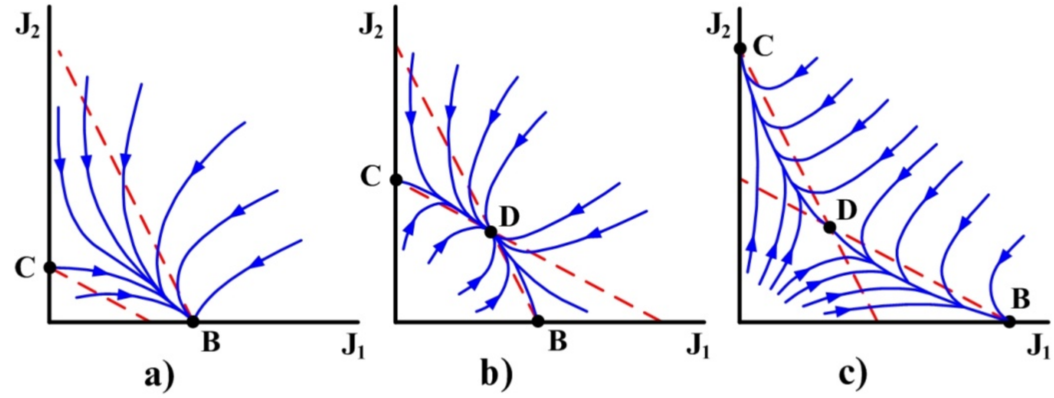


*Figure 1. Competition of two-mode lasers with a homogeneous broaden line and eigenvalues - characteristic points related to the stability of A, B, C, and D, equilibrium points. The conditions of the stationary regime are determined using the points of the intersection [17].*

(This might be further discussed, since it needs to be clarified whether there are any two-level lasers or just masers.).

**Transient regimes** in a generator are treated with introducing normalized coordinates

$$\tau = \frac{t}{T_1} \; , \; \eta = \frac{\mathrm{T}_1}{\mathrm{T}_p} \; .$$

$$\frac{dX}{d\tau} = \dot{X} = \eta X\left(Y - 1\right) \; , \tag{21}$$

$$\frac{dY}{d\tau} = \dot{Y} = Y_0 - Y\left(X + 1\right) \; , \tag{22}$$

where in $X = \frac{|E|^2 T_1 T_2 |d|^2}{\hbar^2}$, $Y = \frac{\varepsilon|\mathrm{E}|^2 N T_p}{2\hbar\omega}$, $Y_0 = \frac{\varepsilon|\mathrm{E}|^2 N_0 T_p}{2\hbar\omega}$. This is followed by testing the stability of the solution and for small deviations from the stationary value; a solution with two algebraic equations resolved by the method of determinants is sought out again. The analysis leads to the phase trajectories and explanations of the damped (relaxation, "amortized") oscillations, the free generation regime, Figure 2.

**Generators with non-stationary parameters**. An unstable mode of operation is possible in the generator, as is established by the analysis of the considered models. Forced modulation of the parameters of the active material or resonator can cause instability of the working regime, if the condition is fulfilled that the ratio of the external disturbance frequency and the frequency of the intrinsic oscillatory instabilities (the eigenvalues frequencies of the oscillating instabilities) is rational.

**Periodic modulation of the generator parameters**. The case of a small modulation depth, $m$, for generators is modeled with the following equations

$$\dot{X} = \eta X \; \left(Y - 1 - m\cos\Omega\tau\right) \; , \tag{23}$$

$$\dot{Y} = Y_0 - Y\;\left(X + 1\right) \; , \tag{24}$$

where $m << 1$, $\Omega = \omega_{mod}\, T_1$. If modulation is perceived as the disturbance, a solution is sought in the form of small deviations from the stationary values.

For generators with modulated quality factor $Q$ (Figure 3.) it should be started from:

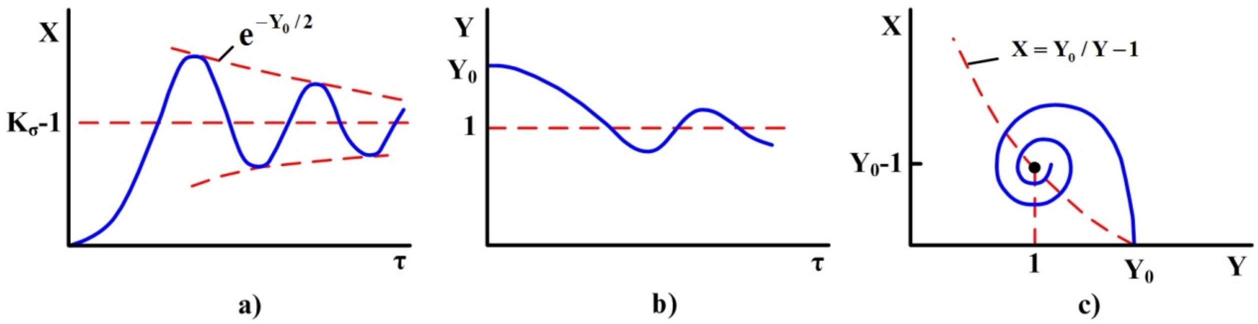


*Figure 2. Transient regimes. Assuming that the conditions defined hold, the stationary point is a stable focus and the oscillations are damped – relaxation oscillations (a, b). If the deviations from the stationary state are non-negligible, the phase portrait of the generator (c) in the mono-mode laser, corresponding to the damped - relaxation oscillations and the phase [17] trajectories is derived.* $X = \frac{Y_0}{Y-1}$. *($K_0 \rightarrow Y_0$).*

$$\dot{X} = \eta XY \quad , \dot{Y} = -XY \quad ,$$

$$X = X_0 + X_1 \exp(i(\Omega\tau)) + kk \quad , \tag{25}$$

$$Y = Y_0 + Y_1 \exp(i(\Omega\tau)) + kk \quad . \tag{26}$$

Neglecting derivatives having small values produces:

$$X_1 = \frac{\eta m(Y_0 - 1)}{2} \frac{i\Omega + Y_0}{\Omega^2 - \eta(Y_0 - 1) - i\Omega Y_0} \quad , \tag{27}$$

$$Y_1 = -\frac{\eta m(Y_0 - 1)}{2} \frac{1}{\Omega^2 - \eta(Y_0 - 1) - i\Omega Y_0} \quad , \tag{28}$$

$$\Rightarrow \quad X = \frac{Y_0}{2}[1 + th(Y_0 \eta(\tau - \tau_0))] \quad , \tag{29a}$$

$$Y = Y_o[1 - th(Y_0 \eta(\tau - \tau_0))] \quad . \tag{29b}$$

**Generators with non-linear losses**. In addition to forced modulation of the resonator and the active material, it is possible to control the dynamics of the operation of the generator using optical elements, within the resonator, whose optical properties can change under the influence of radiation. Nonlinear optical losses are the characteristics of these elements and provide changes in the quality factor $Q$ of working regime. The equations of dynamic equilibrium of this type can be compared to the phenomenological models [18,32] adding the resonator quality factor changes $Q = Q_{max}/f(x)$, where $Q_{max} = \omega T_r$ is the maximum value of quality factor.

$$\dot{X} = \eta X[Y - f(X)] \quad , \tag{30a}$$

$$\dot{Y} = Y_0 - Y(X + 1) \quad . \tag{30б}$$

The stationary equilibrium positions corresponding to the condition $\dot{X} = \dot{Y} = 0$ are obtained through solving these algebraic equations:

$$Y = f(X) \quad , \tag{31a}$$

$$Y_0 = Y(X + 1) \quad . \tag{31б}$$

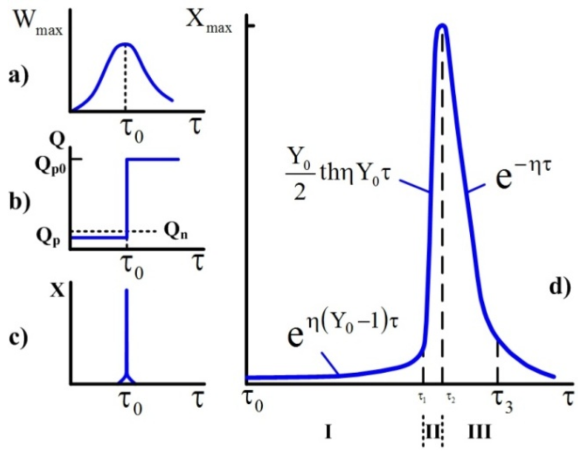


*Figure 3. The regime of developing a giant pulse in a modulated quality factor Q laser generator, which is represented by the behavior of the pump factor, Q, and the shape of the pulse in a small and expanded scale (a, b, c, d).*

If, with the increase of the field, the quality factor Q of the resonator decreases monotonously, additional negative feedback is introduced into the solution providing a stable equilibrium position. Stability analysis is performed analogously to the previous one. The aperiodic regime is implemented in Figure 4. c and d, in case that $\left.\frac{df(X)}{dX}\right|_{X=X_{st}} = \frac{2}{\Omega}$; $\Omega$ is a normalized (dimensionless) frequency of the relaxation oscillations, determined previously. By increasing the quality factor $Q$ of the resonator, an additional positive feedback is introduced, causing that there are several stationary equilibrium positions. If the isoclines are not intersected at the phase level, ($X$, $Y$), generation is not possible. In the case of single cross-section, the equilibrium/position is stable only if the additional feedback is weak:

$$\eta X df(X)/dX + X + 1 > 0 \,\Big|_{X=X_{st}} \quad . \tag{32}$$

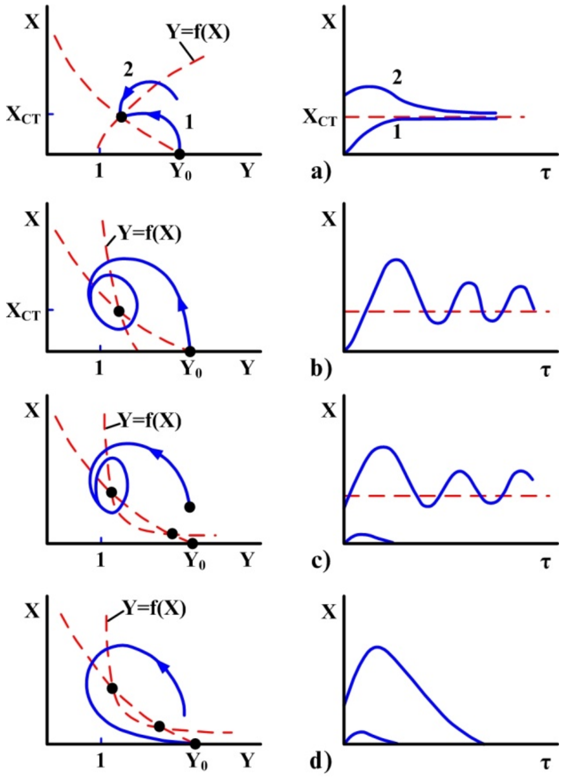


*Figure 4. Phase portrait of a generator with non-linear losses: a) Smooth aperiodic pulse mode with negative feedback, b) Non-damped oscillation mode (RNM) with soft switching of the generator at positive feedback, c) RNM in strong generation mode and positive feedback, d) Strong unstable generation mode with positive feedback [17].*

When there is a reverse inequality, the equilibrium is unstable, the stationary point is perceived as a phase trajectory − a boundary cycle. Generator mode is also possible with the damped oscillations (Figure 4.b). The generator's excitation is soft or weak. There is a condition of auto-excitation, for $X = 0$, $Y_0 > f(0)$. The case when the isoclines are crossed twice represents a system with two non-trivial equilibrium points (Figure 4.b, d). Only the external pulse can now excite a generation, since at $X = 0$, the condition of self-excitation is not fulfilled (a *sharp* excitation). The external pulse, which can excite the generator, must be of higher value than the field, and the saturation of the losses – up to the level of the system's self-excitation. The difference between the soft and strong case of the excitation (switching, generations) is determined by the stability of the first (trivial) equilibrium point $X = 0$. For the strong mode of the switching regime, the steady state is stable and for the soft – it is unstable. The equilibrium point closer to the steady state is not stable (the condition of the auto-excitation exists for this point). Another stationary point of the equilibrium can be stable when the generator is sharply excited and radiates damped pulses or at unstable rate (unstable state). At an unstable equilibrium point, non-damped pulses are possible; a long generation can be maintained in the system (Figure 4.c). Excited by the external pulse, the generator emits a stronger pulse than that and returns to the state of equilibrium or the steady state (Figure 4.d).

**Generators with a non-linear absorption filter** are differing by additional time of relaxation for the filter absorption, so in the expressions there is a notation *ф* and a new system of equations. If the condition for the self-excitation holds, i.e. $Y_0 + Y_{F0} - 1 \geq 1$, and is applied, the generator is softly exited. A general analysis of the stability of the operation of a generator with a nonlinear filter exhibits that the instability of stationary points 1 and 2 exists at $Y_{F0} < 0$. Non-damped oscillations are often occurring in the application of inertionless filters for which $T_F < T_r$ holds (where $T_F$, $T_r$ − specific time parameters related to filters and resonators). If conditions are provided in which a non-linear filter is not saturated before the active material is saturated, then the conditions for giant pulses are reached in the generator. The existence of an unsaturated absorber corresponds to the occurrence of the synchronization of the modes and the radiation regime of ultra-short pulses. (Condition: Y>>1, X<<0), $\xi/\delta >> 1$)

Generators with a non-linear absorption filter relate to generators with non-linear losses, but are studied separately because the relaxation time is included, as well as the absorption time in the filter. Equations (30.a) and (30.b) became

$$\dot{X} = \eta X\left(Y + Y_F - 1\right) \ , \tag{33}$$

$$\dot{Y}_F = \delta Y_{F0} - Y_F\left(\xi X + \delta\right) \ , \tag{34}$$

where $\delta = \dfrac{T_1}{T_{1F}}$ , $\xi = \dfrac{|E|_F^2 \, |d|_F^2 T_{2F}}{|E|^2 \, |d|^2 T_2}$ .

In equation (34), it is taken into account that the material or the filter can be saturated with a field, which is different from the field that interacts with the active medium. The equation system has 3 equilibrium positions. The trivial solution is: $X = 0$, $Y = Y_0$ and $Y_F = Y_{F0}$ and positions 1 and 2.

$$X_{1,2} = 0{,}5\left[Y_0 - 1 + \frac{\delta}{S}\left(Y_{F0} - 1\right)\right] \pm 0{,}5\left[Y_0 - 1 + \frac{\delta}{S}\left(Y_0 + Y_{F0} - 1\right)\right]^{\frac{1}{2}} \ , \tag{35a}$$

$$Y_{1,2} = \frac{Y_0}{1 + X_{1,2}} \quad , \tag{35b}$$

$$Y_{F1,2} = \frac{Y_{F0}}{1 + \frac{\xi}{\delta} X_{1,2}} \quad . \tag{35c}$$

## 3. MODELING THE ANALYTICAL THERMAL FIELD DISTRIBUTION FOR THE SELECTED DYNAMIC REGIME OF THE QUANTUM GENERATOR − LASER

We will consider here the process and problems of estimating the temperature of the active material using the thermal model [8,23]. It starts from the equation for the heating problem with the pumping process, which in general is reduced to the solution for the heat conductivity of the isotropic active material (AM) with thermo-physical characteristics independent of the temperature:

$$\frac{\partial^2 T(t,d)}{\partial d^2} + \frac{1}{d} \cdot \frac{\partial T(t,d)}{\partial d} = \frac{1}{a} \cdot \frac{\partial T(t,d)}{\partial t} \quad , \tag{36}$$

where: $T(t, d)$ is the temperature field, $d$ is the diameter of the crystal, and $a$ − the coefficient of temperature conductivity. It is assumed that the initial and boundary conditions are defined, which depend on the geometric shape of the active material (AM) and the interaction between the surface and the surrounding environment. Heat removal from the laser head is carried out with a cooling liquid of temperature $T_c$ and the coefficient of heat transfer $\alpha$ ($\alpha = 10^3$ – $10^4$ W/m$^2$ K) [8,23]. The heat exchange occurs between pump pulses and the cooling period. This approach, like many other thermal problems, uses a lot of approximations. With boundary conditions

$$\left.\frac{\partial T}{\partial d}\right|_{d_0,t} = -\frac{\alpha}{k}\left[T(t,d) - T_c\right] \quad , \tag{37}$$

a homogeneous equation is obtained [8]:

$$\frac{\partial T}{\partial t} = \frac{1}{d_0}\frac{\alpha}{k}T_c - \frac{1}{d_0}\frac{\alpha}{k}T(t,d) \quad , \tag{38}$$

The heat transfer coefficient between the cooling agent and active material is taken into account as well as the thermal conductivity of the AM. For ruby $k$ = 45-60 W/m·K, and some other thermal parameters for ruby, YAG and sapphire are in Tabs. 1 and 2. The most commonly used data are for the temperature range of 173 K ≤ $T$ ≤ 373 K.

*Table 1. Characteristics of AMs for some laser types*

| Active material (AM) | Concentration of dopant | Melting temperature, $^0$C | Coefficient of expansion $10^{-6}$ $^0C^{-1}$ | Index of refraction |
|---|---|---|---|---|
| Sapphire | 0.0005% | 2040 | 6.7 for $C_{\parallel}$ -5 ($C \perp$) | 1.763(2) |
| Pink ruby | 0.05% | 2040 | „ | 1.736(7) |
| Red sapphire | 0.5% | 2040 | „ | 1.769(7) |
| $Nd^{3+}$:YAG (glass) | 0.1-1.3%, $1.6 \cdot 10^{19}$ * | 2238 | 6.14 | 1.52(1,82) |

* in cm$^{-3}$.

For the range 20−50 $^0$C, the properties of the coefficient of expansion for the various AMs are the same, however thermal conductivity shows differences as in the references. Young moduli, dielectric constants and derivative $dn/dt$ ($12.6 \cdot 10^{-6} K^{-1}$) are the same, but the refraction indices, $n$, are different for the $Al_2O_3$ matrix. The differences in the thermal conductivity of these four active materials determine the quantum efficiency and the thresholds for damaging the alexandrite is at 30 W/cm$^2$. In Table 2 some other parameters for comparison of AMs are given.

*Table 2. Relevant characteristics of the active materials of some lasers*

| Active material | Concentration of dopant, ion | Coefficient of active losses | Coefficient of expansion | Life time for upper level (ms) |
|---|---|---|---|---|
| Ruby | $1.6 \cdot 10^{19}$ | > 0.01 | 23-25 | $3 \cdot 10^{-3}$ |
| $Nd^{3+}$:glass | $1.9 \cdot 10^{19}$ | < 0.006 | 2 | $4 \cdot 10^{-4}$ |
| $Nd^{3+}$:YAG | $2 \cdot 10^{19}$ | > 0.01 | 11-14 | $2 \cdot 10^{-4}$ |
| Alexandrite | 0.05 – 0.23 ** | < 5 *** | | $1.74 \cdot 10^{-4}$ * |

* For range (250nm – 2.6μm)
** at%
*** in dB/km

It is initially assumed that in case of a rapid increase of the temperature of AM, at each pump pulse, the temperature changes for $\Delta T_i = \frac{a}{k}E(T)$ which depends on the heat energy removed from the crystal, $E(T)$.

$$T(0,d) = T_c + \frac{a}{k}E(T) \quad . \tag{39}$$

The function $T(t, d)$ is determined from the conditions of heat exchange. With the initial and boundary conditions according to (36), the temperature field is derived. For the start of the pump operation ($n = 0$), the AM temperature is equal to the temperature of the cooling agent ($T_0 = T_c$). The solution of the thermal conductivity equation during the time interval $0 \le t \le t_0$ is suitable to be expanded into series [8],

$$T(t,d) = T_c + \frac{a}{k}E(T)\sum_{n=1} A_n J_0\left(\mu_n \frac{d}{d_0}\right) exp\left(-\mu_n^2 \frac{a}{d_0^2} t\right) \tag{40}$$

where $\mu_n$ is the $n^{th}$ root of the characteristic equation, $A_n$ is the coefficient taken from the table, which depends on the criterion $BiO$ ($Bi = \alpha l(k)$ 3 characteristic efficiency of the heat exchange), $J_0$, $J_1$ − Bessel functions of the first kind, of the zeroth and the first order. After some time and a certain number of pump pulses, AM is heated and a constant temperature is reached on the surface of AM. The boundary conditions for all intervals: $0 \le t \le t_0$, $t_0 \le t \le 2t_0$, $2t_0 \le t \le 3t_0$, …, $(n - 1)\, t_0 \le t \le n\, t_0$; are determined by (37), and the initial conditions for each subsequent time interval, related to the temperature of the crystal AM at the moment of $n^{th}$ pulse of flash lamps are determined from: $T(nt_0, d) = -\varphi_1[d, (n - 1)\, t_0]$,... After substitutions of variables are made for each interval, the following is obtained,

$$T(t,d) = T_c + \frac{a}{k}E(T)\sum_{n=1}^{\sim} A_n J_0\left(\mu_n \frac{d}{d_0}\right)e^{-\mu_n^2 \frac{a}{d_0^2}t} + \frac{a}{k}E(T)\sum_{n=1}^{\sim} A_n J_0\left(\mu_n \frac{d}{d_0}\right)e^{-a\frac{\mu_n^2}{d_0^2}(t-t_0)} + \cdots$$
$$\cdots + \frac{a}{k}E(T)\sum_{n=1}^{\sim} A_n J_0\left(\mu_n \frac{d}{d_0}\right)e^{-a\frac{\mu_n^2}{d_0^2}(t-nt_0+t_0)} \tag{41}$$

These results are given for the case of heating any active material (Figure 5) and these can be qualitatively applied to heating the common types of solid state lasers. The next task would be to determine the frequency for the pulse laser, especially for each group, where the solutions are obtained as before, assuming the thermal conductivity equation holds and calculating the stabilization temperature:

$$T_{st} = T_c + \frac{a}{k}E(T)\sum_{n=1}^{\sim} \frac{A_n J_0\left(\mu_n \dfrac{d}{d_{\max}}\right)}{\exp\left\{a\left(\dfrac{2\mu_n}{d_0}\right)^2\left[\dfrac{1}{f} - \dfrac{n+1}{f_1}\right]\right\}} \tag{42}$$

One approximation leads to the formula:

$$f_g \approx \frac{32\, Bi\, a}{\dfrac{d_0^2}{4}(4 - Bi)\ln\left(1 - \dfrac{1}{\delta_e}\right)} \quad , \tag{43}$$

where $\delta_e$ = 1.01 ... 1.1, for the criterion $BiO$, which changes from 2 − 10 mm. This approach should solve the task of designing and calculating the cooling system next, with various solutions available [8,23].

By using MATLAB 7.5, the approximation of sum is made taking the finite number of terms in series, using the solution for the roots of the characteristic equation. The energy of the pump, $E_p = U^2C/2$, was taken as 60 J. The pump produces energy in the active material at discrete moments of time with a period of $t_o$ of 1s or the frequency of 1Hz. Each pulse of the optical pump corresponds to the induced radiation pulse. The heat exchange is calculated only through the cylindrical surface of AM while the exchange through AM faces is neglected (~ 6%). The change in quantum efficiency at the moment of radiation is considered to be a quasi-stationary process. The pumping of AM pumps takes place faster than heat exchange between adjacent locations. We have calculated the temperature change in the case of four pumped pulses (corresponding to generating four laser pulses) at moments $t$ = 0, 1, 2, 3. The graph for the period 0-5 s is given in Figure 6. Temperature is given in K.

After the last, the $4^{th}$ pulse, the active material is suddenly cooled by the circulation of the coolant.

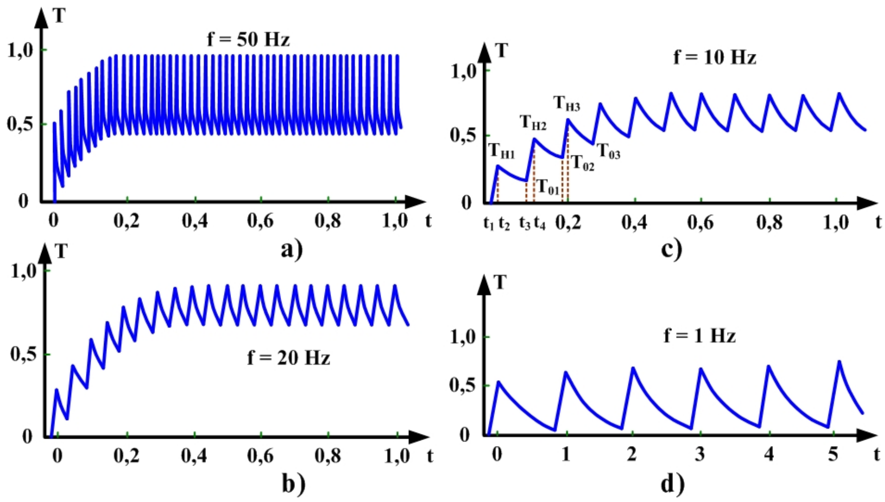

*Figure 5. Temperature field (in relative units) at a certain place of ruby crystals measuring 8 x 0.8 cm in time $\alpha = 10^3$-$10^4$ W/ ($m^2$K): a) f = 50 Hz, b) f = 20 Hz, c) f = 10 Hz, d) f = 1 Hz, respectively [8].*

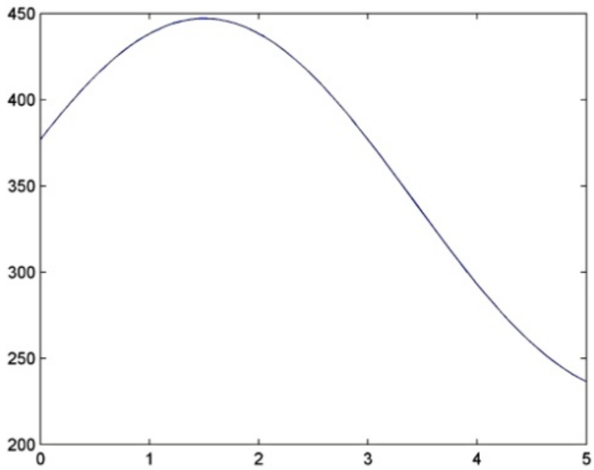

*Figure 6. Graph of the temperature change with time in the active ruby material due to pumping, pulse propagation and cooling.*

There is also a graphic-analytic calculation [11,24] of the constructive parameters of pulse lasers and energy characteristics with the calculation of the coefficient of efficiency, cross-section and length of AM, selection of flash lamps (pumps), gain coefficient, number of pump pulses (Figure 7). The graphic-analytic approach gives a nomogram of constructive parameters, spectral characteristics, and radiation characteristics.

The second group of authors proceeds in a similar way, but formalisms and classifications are different, although the formalisms of quantum mechanics and calculation of the transitions of various orders are respected, etc. Table 3 gave an introductory approach to laser theory as in [25].

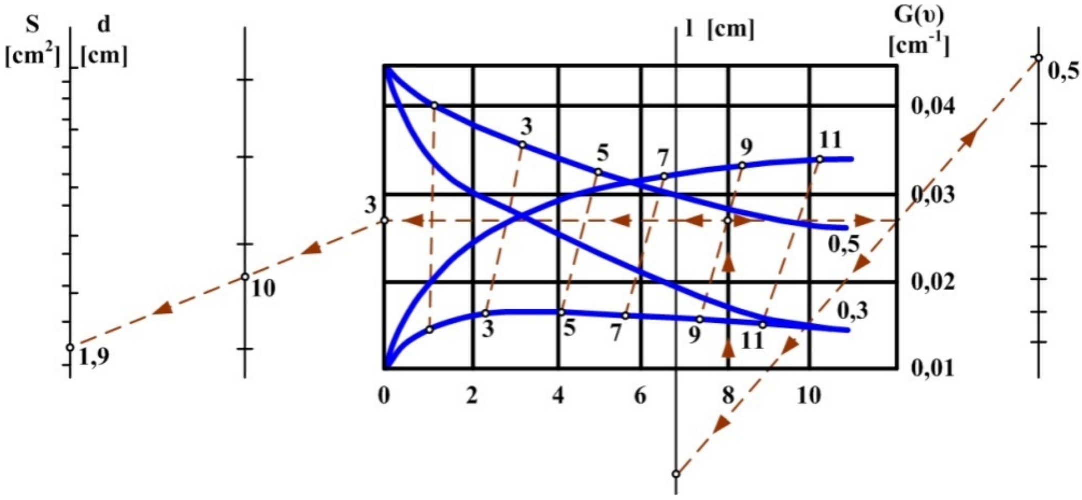

*Figure 7. Nomogram of calculation of constructive parameters of lasers on a solid state laser [8]. (The second vertical corresponds to the energy (J) and the last right corresponds to diameter)*

*Table 3. Characteristic approach to the lasing process [25]*

| Number | Stationary intensity | Configuration |
|---|---|---|
| 1 | $\frac{N£-1}{£}$, | One-directional ring, integral equation 16 (p.175 [26]) |
| 2 | $\frac{4}{3}\frac{N£-1}{N£^2}$, | III order standing waves equation 19 [25] |
| 3 | $\frac{N£-\frac{1}{4}-\frac{1}{4}(10N£+1)^{1/2}}{£}$ | Exact standing waves from equation 18 [26]. |
| 4 | $N^2\exp 2\left[-\frac{2(w-v_n)^2}{(w)^2}\right]-1$ | One-directional ring, integral equation 16 (p.175 [26]) |

## 4. THE ANALYTICAL MODELLING OF THE SEMICONDUCTOR LASER

A number of various scientific journals were often dedicated to lasers, theory, application, major problems, and semiconductor lasers [26]. We will mention only a part of the equations applied to one approach and an equivalent scheme in semiconductor material, Figure 8a, b. The system of 18 equations describes the dynamics of potential, population, energy, and other parameters, which are included in stimulated processes for semiconductors:

$$\nabla^2\phi=0 \quad , \tag{44}$$

$\phi$ – contact potential,

$$\phi(0.y)=\frac{1}{e}\left(E_g+\varepsilon_c(N(y))+\varepsilon_v(N(y))\right) \quad , \tag{45}$$

$$\rho J(y)=\left.\frac{\partial\phi}{\partial x}\right|_{(0,y)} \quad . \tag{46}$$

The equations e. g. differential equations of the second order for population, differential equations of the 1st order for amplitude modes, efficiency, gain, etc. are presented in Table 4.There are given semi-consistent laser models [26], which are organized according to various authors and years ($\tau$ – time of life).

*Table 4. Modeling semiconductor structures of various authors [26]*

| **Models** | **Diffusion equation** | **Guiding** | **Solution for fields** | **Results** |
|---|---|---|---|---|
| 1. Chinone | Bimolecular recombination Simple case | Only gain, possible asymmetry | Perturbation | Nonlinear characteristics |
| 2. Thompson | Constant $\tau$, simplified profile of intensity | Real and imaginary parts proportional to concentration of carrier, self contribution | Fitted with Gaussian (shifted and tilted) | Nonlinear characteristics, shift of near field |
| 3. Seki | Constant $\tau$, simply spreading of current | Only gain, symmetry | Galerkin | Reduced efficiency on large powers |
| 4. Lang | Constant $\tau$, simply spreading of current | As in 2. | Variation | As 2. |
| 5. Asbeck | Constant τ, the problem of junction is considered | As in 2. And symmetry | Finite difference methods | Nonlinear characteristics, exchange of far field |
| 6. Buus | Constant $\tau$, simply spreading of current | As in 2. + thermal contribute, symmetry | Galerkin | Nonlinear characteristics, mode of first order |
| 7. Shore | As in 1. And the problem of junction | As in 5. without symmetry | Transversal resonance | Asymmetric solution for symmetric structures |
| 8. Streifer | As in 3. and non-planar active layer | Real and imaginary parts proportional to concentration of carrier, symmetry+self contribution due to geometry | Direct integration | Detailed comparison with experiment |
| 9. Wilt | Junction and non-planar active layer | As in 8. | Method of finite differences | I/V characteristic, current-voltage, modes of higher order |

| Models | Diffusion equation | Guiding | Solution for fields | Results |
|---|---|---|---|---|
| 10. Su | Constant $\tau$, constant current | As in 2. | Similar as in 2. | As in 2. |
| 11. Machac | Constant $\tau$, simply spreading of current | As in 3. | Galerkin | Spectrum as function of current |
| 12. Buus | Constant $\tau$, simply spreading of current | As in 2. | Stepwise | As in 6.+ shift of near field |
| 13. Baets | Constant $\tau$, simply spreading of current | As in 2. | BPM | Longitude effects |

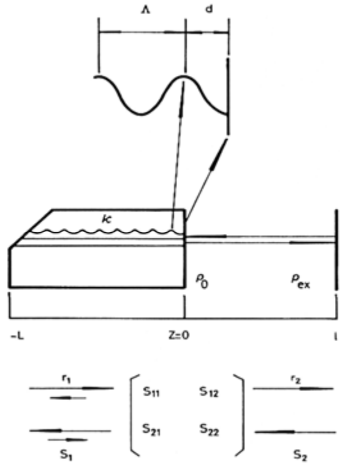

*Figure 8a. Physical model (for Table 3.1).*

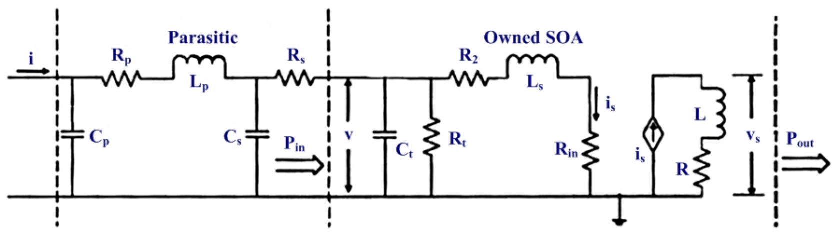


*Figure 8b. Model of lumped circuit for small SOA signals. [27]*

## 5. MODELING OF SEMICONDUCTOR LASER WITH ELECTRON BEAM PUMPING

The modeling of semiconductor lasers by nuclear particles pumping have to start from energy loss equations (for either light or heavy particles), while for electron beams of relativistic velocities Bethe's [27−31] or similar formula holds.

The next stage is related to the range of the pump beam for specific materials based on the experiment and phenomenological formulas, describing kinetic energy and the dependence of the range vs. energy for the particle. Then, following are the models containing laws of solid state physics or models from the field of achieving population inversion in semiconductor material. In other lasers with pumps from the *nuclear area*, either complex and lengthy calculations are performed using programs with neutron distributions and a lasing threshold obtaining, or in case of gamma-rasers, special expressions for Einstein's coefficients in the nuclear field are included. (These are based on the probability of transitions between nuclear levels – i.e. on nuclear spectroscopy formalism.)

$$-\frac{dE}{dx}=\frac{\pi N e^4 Z}{m_e v^2}\left[\ln\frac{m_0 v^2 E}{2I\left(1-\beta^2\right)}-2\left(\left(1-\beta^2\right)^{\frac{1}{2}}-1-\beta^2\right)\ln 2+\frac{1}{8}\left(1+\left(1-\beta^2\right)^{\frac{1}{2}}\right)\right] \quad . \tag{47}$$

For Brillouin type lasers, a specific term in the probability of transition arrives, which will determine either the Einstein's coefficients or the specific adapted probability of transitions and cross sections, or the lasing threshold. So there exists Raman scattering both in the nuclear field, as well as in atomic. Soliton laser is often related to fibers and it follows the corresponding formalisms, with time delays, and the choice of white or black solitons, etc., and the theory and equations developed as in [33].

Technically, for each type of laser, a list of questions and issues should be compiled: advantages, disadvantages, emission characteristics, efficiency, frequency characteristics, spectral range of the channel, stability (frequency, beam diameter, divergence, emission direction), compatibility, operating requirements, cooling system, accessories, operating conditions (pressure, temperature), mechanical characteristics, reliability requirements, maintenance, mechanical robustness, possible failures, commercial devices, main and specialized applications, cost and deep theoretical breakthrough. It would be of further interest to compare the historical prediction of how the quantum generators should work in various portions of the EM spectrum, the range of tuning by $\lambda$, the pulsed and continuous devices, or the counting of the number of stimulated transitions achieved by using nonlinear frequency transformations, including parametric, semiconductors, $F$ – center, spin-flip and modern lasers with quantum wells and of other structures, *lasers without population inversion*, and others.

## 6. PROGRAM PACKAGES FOR THE DESIGN − CHARACTERISTICS OF QUANTUM GENERATORS

Analytical and numerical aspects (with or without the use of computers), regarding issues and problems of a general or specific nature and the application of a particular type of laser are the subjects of many references [1-20, 34-42]. In Figs. 9−17, simulations are presented in relation to selected cases with the application of the program package or programs in the references for specific types of lasers, proximity to the threshold, parametric generators, and similar topics. The applications require a precisely defined shape and performance of a beam, a dynamic mode, and similar. Various elements perform transformations by means of form, power, polarization, etc. In a developed system with a laser (measuring, processing, energy), the linear set of elements on the beam's path has its own reality in application. On the basis of various theories, in cases where matrix optics and analytical methods are applied, much is accomplished with the models of semiconductor lasers. There is a number independent program packages that focus on individual task groups, which can also fit into the GLAD and ZEMAX programs for beam propagation, focusing, that are used to transform the beam, quantization, filter, change the parameters of the resonators, and stabilize the process. [43-49].

The LASCAD software package (available in several versions) can be used for calculating the characteristics of quantum generators, for shaping, beam correction, parameter search, optimal mode, resonator shape, 3D distribution of temperature fields, deformations, and stresses of active materials using Finite Element Method (FEM). The results are displayed as 3D color images. LASCAD follows the wave front and the distribution of the intensities of the beam through the resonator and outside it. The software compares the properties of various AM selections to the input data within an existing, expanded or custom database with realistic features. Unified Algorithms and Beam Propagation Methods (MPS) determine the shape and non-Gaussian modes and simulate the properties in various representation or optimization tasks. The LASCAD software package, developed by Micro Systems Design (MSD), and Daimler-Benz, supports simulations for integrated and diode-pumped lasers on solid objects – DPLCT and various optical effects [1-20, 50-52]. It runs under the Windows operating system and has developed software for the application on the thermal model, monitors the AM distortion, the design of microchips and more powerful lasers on the solid state LCR.

The propagation of the beam through a material equivalent to a thermal lens is often the case, with realistic absorption. Simulation of the Gaussian beam propagation through the material (in the function of a waveguide) for various refractive index values - $n_2$ can be made using the program packages and various mathematical models in MATLAB. These are parts of the simulation: propagation of the laser beam through a real-medium, the lens, the definition of the complex refractive index n, in the non-homogeneous area, the distortion, and is propagation parallel to the position of the Gaussian beam to the axis of the waveguide, the two parallel Gaussian beams, 2D and 3D representations for n, the radial distribution of energy per X and Y-axis. The simulation of a single-step laser amplifier in MATLAB was done, with a general approach by definition of the Long pulses LP Gain function with a single-layer model, defining field outputs, listing programs in the case of saturation in 3D geometry, etc.

The characteristics of the unstable resonator and the modal structure, Figure 10, with random noise, random path diagrams, intensity distribution in 3D (and 2D) in the area of far-field and near -field zones, are also simulated, and the processes on the interface defined by the refractive index are also taken into account. There is a list of programs and the layout of main screen with the user interface for computing programs, written in the Microsoft Visual Basic 6.0 environment.

Various packages take into account the configuration, dynamic laser modes and conversion of passive material to AM, along with the pump selection. There are technical differences in pump selection. The selection of the active material, the type of laser and the method of pumping is done according to the criterion of the completeness of the implementation of the law on the example of a modern laser. The application of standards and measures of protection are covered by specific references, and there are also calculations for special components (Beam splitter and Beam expander).

This is also covered by the high power of the pump. Simulations are often simplified due to the complexity of the process with nonlinear effects, higher order harmonics, and so on. Simulations are done on a PC, with a graphical interface. Different distributions of the refraction index are simulated. Software for assessing the resistance of materials to radiation and optimal design has been developed.

The amplification control is another problem that occurs with residual stresses, crystalline deformations, changes in the dimensions of the material components, new modal distributions, and birefringence; there is also a simulation of explosive processes or cracks.

Resonators are virtually assembled on the screen by inserting and positioning optical elements (lenses, mirrors, plates, filters, etc.). The input power, wavelength, distribution of the intensity of the pump beam and parameters (thermal conductivity, expansion and *impurity* level of the crystal) are given. The wave front and the modulation intensity distribution are simulated, based on ABCD matrix approach with parabolic approximation for heat exchange and gain adjustment, as a prerequisite for conversion power and generator efficiency. A database with existing AM (with ions $Nd^{3+}$, $Er^{3+}$, $Y^{3+}$, $Ho^{3+}$, and YAG matrices and glasses) is made. A user's task would be the filling of base with data, according to newly developed types of active materials. The software compares the properties of various crystals by comparing the input data from the database with real data gained from new samples of materials. Unified algorithms of the beam propagation method are used. They will determine the shape of Gaussian laser modes more precisely and simulate the properties of the beam propagation in various presentations. It is based on lasers that can be color standards (RGB).

An interface with the ray tracing code is provided, which is written in the ZEMAX [46] software package and numerical method for defining the density of the absorbed pump power distribution and analysis of fast regimes. The earlier versions of TracePro [13, 44] are also used for the interface with ray tracing code. A multiphysic simulation of the resonator design is performed, as well as 3D analysis of the nonlinear interaction of thermal and optical fields, the effect of thermal lens as a disturbance in guided amplification devices and other effects for controlling beam quality and productivity for more complex cases. Numerical analysis of the effects is important for the trend of miniaturization of components and increase of output power in case of interactions with strong fields in small volumes. It is a software for industrial applications, which combines simulation tools for modeling the most important effects. They are compensated and controlled by the required hardware changes.

The results are related to the size of the spot in the selected operating mode, with inclusion of Hérmite-Gaussian polynomials [44]; astigmatism [18] is taken into account in two planes normally to the axis of the resonator.

The main windows of LASCAD are displaying data from the resonator (with four elements) with standing waves and parameters, Figure 13. There are elements that characterize the parameters (radius of curvature for each mirror). To change the type of element, the boxes for selecting elements (dielectric interface, lenses) are used. Locations of elements, refraction changes, incident angles, amplification are defined. Some of the problems are the cylindrical active material, as well as the lateral pumping and longitudinally, the selection of the crystal, the type of pump and the configuration. In Figure 9 is shown an illustration of program package with astigmatism [18]. The active material is pumped from one facet, in the „top hat“ output, along the z axis and with super Gaussian shape ($\perp$ on z axis). It is possible to simulate various cases: double and end pumped active material, AM and rectangular geometry AMPG, AMPG with pump that provides a „top hat“ beam shape (|| z axis) and super Gaussian shape ($\perp$ on axis), AMCG pumped from one side (from sandwich configuration side), AMCG rod with numerical input of pump energy distribution, AM with numerical input, AMCG pump „from end“ etc.

The simulation of the cooling system includes matrix optics. There is a detailed description of the pump beam path from one element to another, between the elements, the circulation, the reflection, etc. Therefore, reflection, refractive index, curve radii, cooling tubes are required. Gaussian algorithm includes the coherence of the beam, so it is better than other *ray tracing* type solutions. After passing a large number of elements, the accuracy decreases, while spherical aberration is not included.

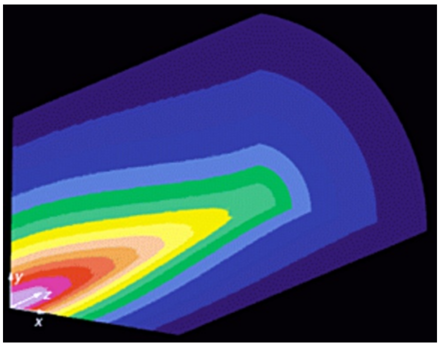


*Figure 9. Visualization of the temperature field in the AM section, frontal pumping.*

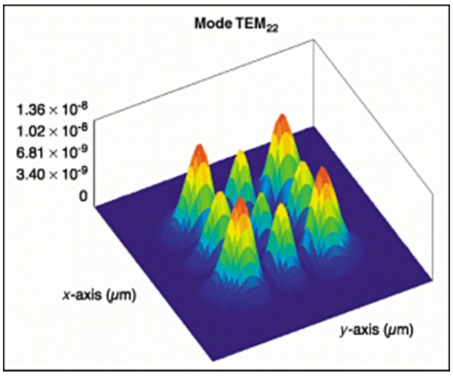


*Figure 10. Analysis using Hérmite-Gaussian $TEM_{22}$ mod.*

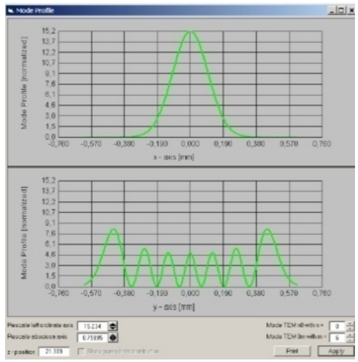

*Figure 11. Gaussian profile and higher order modes.*

Defining the cooling of the active material of the cylindrical geometry, with a simple law, is given by $I = I_0 \exp(-\alpha z)$. The cases of lateral pumping of complex materials and controls for finite element analysis (FEA) procedures are also considered. Convergent processes of iterative boundary procedures are monitored. According to the convention, $10^{-7}$ was adopted as ending point to stop the thermal analysis code, if the maximum temperature is unchanged in the first 7 digits. The boundary for structural analysis refers to the absolute value of the maximum nodal step T.

LASCAD uses two tools to visually represent FEA results, Figure 14. Parabolic double adjustment is also used. When calculating Gaussian modes, the adjustment is possible for all subsections along the crystal, using the FEA networking procedure. The crystal is divided into graded index (GRIN) series of lenses, with its own parabolic index distribution. Deformations are also simulated by fitting the radius of the curvature of the astigmatic spherical surface to the facets.

The display of the normal mode of Gaussian profile is related to the transversal pump profile and laser transversal modes for lateral and longitudinal pumpings. When BMP modulation propagates, parabolic approximation and matrix code ABCD are not sufficient. FEA results can also be used as input data for waves and propagation problems. The codes use 3D wavefront simulation, propagated through a hot deformed AM, without parabolic approximation, at the right end, and the second convergence of the radius of the beam with an increase in the number of iterations in the resonator. Output power is always an important parameter that is being evaluated. Some other examples of simulation with the appearance of beam intensity and visualization of FEA results with multiple tools are given (Figs. 11−17).

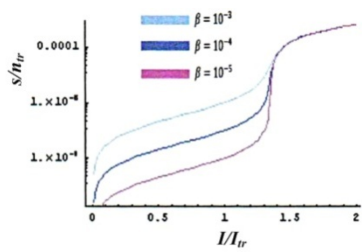


*Figure 12. Results of the program in the vicinity of the lasing threshold.*

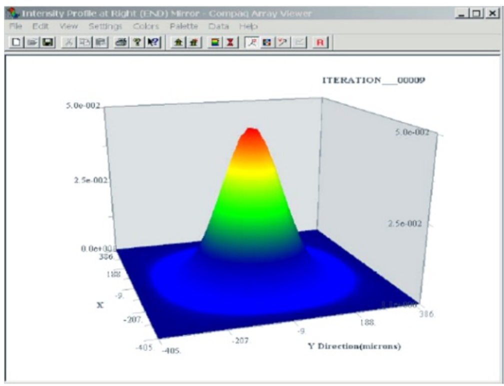


*Figure 13. Mode propagation at the end of AM.*

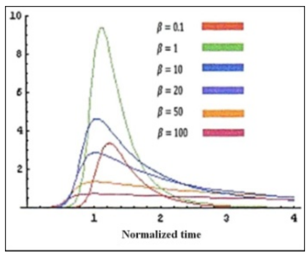


*Figure 14. Simulation of parametric processes.*

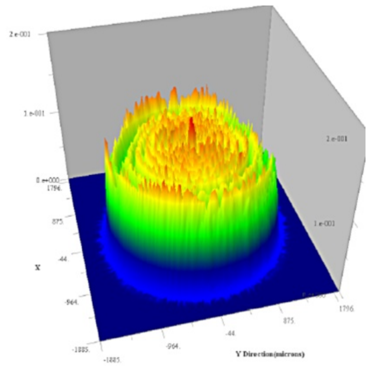

*Figure 15. BMP Multiple Case.*

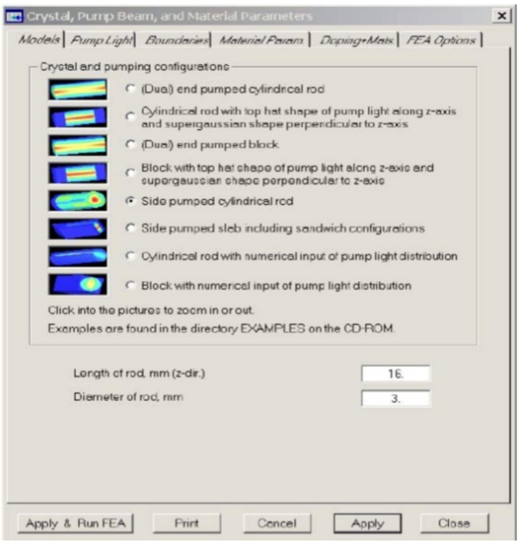


*Figure 16. Screen with simulation options.*

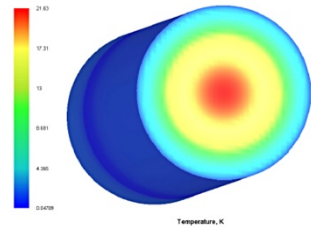

*Figure 17. Visualization FEA, Temperature (T) distribution.*

7. CONCLUSION

The field of laser technology and quantum electronics together with material science represents a very dynamic field with many different approaches, experiments and theories based on classical fundamental sciences related to application. However, it is correctly based solely on quantum mechanical concepts and with nonlinear optics and many different phenomenological approaches since it has emerged from the *crossroads* of sciences and it has immediately taken its own *path* after inception. Analytical approaches, in which numerical analysis have to be included are in accordance with the degree of complexity, the capabilities of the computer system, and require long computing time for certain problems. The most sophisticated approaches are related to the achievement of a degree of coherence as high as possible and its description. Studying the modal structure, creating an interface to make link to the more general or more specific algorithms developed, forming a dedicated database, all this can be considered in a future development of theory and applications. The development of numerical approaches and simulations using program packages had enabled quick estimates and the possibility of checking further the sophisticated theories and confirming or matching with the experiment. Experiments related to the large energy projects, short pulses and mixing of the EM spectrum ranges (atomic-nuclear-optics) are fused by the principle of population inversion. There is much work yet to be done in this area, because the experiments are related to large scope projects, that are developed on a worldwide scale and with international cooperation. For the commercial types of quantum generators too, there are concepts of high power densities and the development of nonlinear effects applications, and this certainly holds for the short pulses, transient regimes, threshold issues, where the theory and the results of the experiments are constantly predicted, compared and analyzed. In numerical and analytical approaches, questions often arise whether the certain assumptions are correct from the perspective of the reality field and the rigorous mathematical concepts. Converged processes are particularly important regarding the shortening of the pulses and problems arise even when nearing nano- and pico-seconds.

8. REFERENCES

[1] N. G. Basov, G. D. Hager, A. A. Ionin, A. A. Kotkov, A. K. Kurnosov, J. E. McCord, *Efficient Pulsed First Overtone CO Laser Operating Within the Spectral Range of 2.5-4.2*, IEEE J Q E,Vol. 36−7 (2000) 810−823.

[2] J. E. McCord, A. A. Ionin, S.P.Phipps, P.G.Crowell, A.I.Lampson, J.K.McIver, *Frequency-tunable optically pumped carbon monoxide laser*, IEEE J Q E, Vol.36−9 (2000) 1041−1052.

[3] A. A. Ionin, I. O. Kinyaevskiy, Y. M. Klimachev, et al., *Cascaded carbon monoxide laser frequency conversion into the 4.3–4.9 µm range in a single ZnGeP 2 crystal,* Opt. lett., Vol. 37−14 (2012) 2838−2840.

[4] A. A. Ionin, I. O. Kinyaevskiy, Y. M. Klimachev, A. A. Kotkov, *Frequency conversion of radiation of IR molecular gas lasers in nonlinear

*crystals*, A rev.Opt.& Spectr., Vol. 119−3 (2015) 356−362.

[5] Y. M. Andreev, O. V. Budilova, A. A .Ionin, I. O. Kinyaevskiy, Y. M. Klimachev, *Frequency conversion of mode-locked and Q-switched CO laser radiation with efficiency up to 37%*, Opt. Lett., Vol. 40−13 (2015) 2997−3000.

[6] A. A. Ionin, Y. M. Klimachev, A. Y. Kozlov, A. A. Kotkov, L. V. Seleznev, *Pulsed electron-beam sustained discharge CO laser on oxygen-containing gas mixtures*, Quant. Electr., Vol. 38−2 (2004) 115−124.

[7] V. D. Zvorykin, N. V. Didenko, A. A. Ionin, I. V. Kholin, A. V. Konyashchenko, *GARPUN-MTW: A hybrid Ti:Sapphire/KrF laser facility for simultaneous amplification of subpicosecond/nanosecond pulses relevant to fast-ignition ICF concept,* Laser and Particle Beams, Vol. 25−03 (2007) 435−451b.

[8] Yu. V. Baiborodin, *Laser Technique,* Visča škola, Kiev, (In Russian), 1981.

[9] I. R. Chen, *Principles of Nonlinear optics*, Mir, Moscow, (in Russian), 1988.

[10] A. Tarasov, *Laser Physics,* Mir, Moscow, (in Russian), 1983.

[11] M. Srećković, *Solved problems and examples in Quantum electronics*, Građevinska knjiga, (in Serbian), Belgrade,1993.

[12] M. Srećković, S. Ostojić, S. Ristić, J. Ilić, V.Arsoski, *Solved problems and examples in quantum electronics, laser techniques and neighboring areas and application*, Technical Faculty, Čačak, 2007.

[13] I. Pahomov. A. B. Cibulya, *Design of optical systems of lasers devices*, Rad i svyaz, Moskva, 1986.

[14] A. Yariv, *Optical electronics*, CBS College Publishing, New York, 1985.

[15] J. T. Verdeyen, *Laser Electronics*, Prentice Hall, Englewood, Cliffs, New Yersey 0763, 1995.

[16] M. Srećković, *Scripta from laser technique*, Int.material, *2007.*

[17] G. L. Kiselev, *Devices for quantum electronics*, Vissaya škola, (in Russian), Moscow, 1980.

[18] E. Rosencher, B. Vinter, *Optoelectronics*, Cambridge University Press, Cambridge, 2002.

[19] *Optoelectronics, quantum electronics and applied optics,* (in Russian), Mecniereba, Tbilisi, 1983.

[20] A. E. Siegman, *Lasers, Mode calculations in unstable resonators with flowing saturable gain: 2. Fast Fourier transform method*, Appl. Opt., Vol.14 (1975) 1874−1889.

[21] b) A. E. Siegman, Lasers, Oxford: Oxford University, 1986.

[22] W. E. Lamb, *Theory of Optical Maser*, Phys. Rev., Vol.134−A (1964) 1429−1450.

[23] J. W. Goodman, *Introduction to Fourier Optics*, McGraw-Hill, 1968, 49−56.

[24] M. Srećković, V. Zarubica, A. Janićijević, S. Jevtić, M. Dinulović, V. Fotev, et.al., *Materijali za savremene kvantne generatore i komponente,* Conference Proceedings „Contemporary Materials“ Banja Luka, 2012, 157−189.

[25] J. Kaplan, *Designing Lasers with Pumped Power Charts Electronics*, Vol.36−52 (1963) 9−16.

[26] P. Mestre, M. Sargent, *Elements of Quantum Optics*, Springer, Berlin, 1985.

[27] IEE Proceedings, J, Optoelectronics, Vol. 132−1, Part J, February 1985.

[28] H. Lv, Z. Li, T. Yang, Ch. Huang, *Small-signal circuit modeling for a semiconductor optical amplifier monolithically integrated with a sampled grating distributed Bragg reflector laser*, Opt.Applic., Vol.42−1 (2012) 56−68.

[29] O. V. Bogdankevič, S. A. Darznek, P. G. Eliseev, *Semiconductor laser,* Nauka, (In Russian), Moscow, 1976.

[30] G. P. Agrawal, N. K. Dutta, *Long Wavelenght Semiconductor Lasers*, Van Nostrand, New York, 1986.

[31] M. Srećković, *Stimulated effects of electromagnetic radiations, particles, quantum generators, and nonclassical excitations sources*, Eng.Phys.,Vol.26 (1985) 66−77.

[32] N. Kartalović, K. Stanković, N. Zdjelarević, I. Knežević, *Radation compability of electrical components and devices,* Zavod za fiziku tehn. fakulteta, El.Inst. N.Tesla, (In Serbian), Belgrade, 2016.

[33] B. Veselinović, M. Srećković, I.Veselinović, *Laser Modeling in Q switch Regime*, ICEST, Ohrid, 2007.

[34] M. Srećković, *Problems and nonspecific effects of fiber optics in view of linear and nonlinear phenomena*, Fibers and Sensors, SITJ, (In Serbian ), Belgrade, 1991, 294−324.

[35] S. Alam, *Lasers without Inversion and Electromagnetically Induced Transparency*, SPIE Press, Bellingham, 1999.

[36] M. Srećković, *Lasers technique*, Sprint, (In Serbian), Novi Sad, 1998.

[37] M. Srećković, B. Kaluđerović, A. Bugarinović, M .Janićijević, *Laser interaction and textile and carbon material characterization by laser*, StudioM, (In Serbian), Belgrade, 2015.

[38] M. Srećković, I. Đurđević, B. Veselinović, *Design in laser techniques and quantum electronics theory and appl*ications, Monograph Faculty of Techn. Sci. FTN, Machine design, 2008, 335−361.

[39] I. Veselinović, M. Srećković, B. Veselinović, A. Đurđević, B. Stojković, *Analyzis of nonlinear efficiency of conversion frequency*, YUINFO, Kopaonik, 2007.

[40] I. Veselinović, *Coherent Light effects to selected organic materials*, Master Thesis, Faculty of Electrical Engineering, University Belgrade, (In Serbian), 2009.

[41] B. Veselinović, M. Srećković, I. Veselinović, M. Vlajnić, *Modeling of Semiconductor Laser Characteristics*, YUINFO, Kopaonik, 2007.

[42] I. Veselinović, M. Srećković, B. Veselinović, A .Đurđević, B. Stojković, *Nonlinear Frequency Conversion Efficiency Analysis*, YUINFO, Kopaonik, 2007.

[43] B. Veselinović, M. Srećković, I. Veselinović, M. Vlajnić, *Modeling of Quantum Generators and Amplifiers on Semiconductors Materials,* ICE-SR, Ohrid, 2007.

[44] M. Srećković, B. Đokić, A. Kovačević, *Numerical principles and problems in the design and implementation of some modern quantum generators, m*achine design, FTN, Ed. S. Kuzmanović, Novi Sad, 2009, 63−68.

[45] B. Đokić, *Technical and Measuring Aspects of Handling, Shaping and Corrections of Laser Beams*, Master Thesis, Faculty of Electrical Engineering, University Belgrade, (In Serbian), 2005.

[46] B. Đokić, M. Srećković, A. Kovačević, J. Mirčevski, N. Bundaleski, *Applications of programme packages for laser beam shaping and their role in education*, 51.Conf. ETRAN 2007, (CD), 2007.

[47] www.zemax.com

[48] www.physics.ncsu.edu/pira/6optics.

[49] www.las-cad.com

[50] www.bluelaser.com.

[51] B. F. Belostockij, Yu. V. Ovčinikov, *Basics of laser technique*, Sov.radio, 1972.

[52] A. M. Kugushev, N. S. Golubeva, *Principles of Radioelectronics*, Mir, (in Russian), Moscow, 1979.

[53] H. Haken, *Light*, North Holland, Amsterdam, 1985.

ᢒᢓ

## ФОРМАЛИЗМИ, АНАЛИТИКА, РЕЗУЛТАТИ И ОСТВАРЕЊА СА ИНВЕРЗИЈОМ НАСЕЉЕНОСТИ МАТЕРИЈАЛА

**Сажетак:** За шест деценија квантне електронике, развијено је много нових врста квантних генератора, који су обухватили цео електромагнетни спектар. Иако је принцип инверзије насељености ујединио разне делове ЕМ спектра и типове квантних генератора, постојање наслова о ласерима без инверзије насељености чини да изузетак потврђује правило, односно да овај назив заслужује дискусију. При развоју формализама за дескрипцију рада квантних генератора постоји данас неколико прилаза, који морају да имају квантно- механичку базу. Из практичних разлога, негативни коефицијент апсорпције добија се и путем класичне електромагнетике, али се путем (помоћу инверзије) насељености улази у квантне представе.

У раду ће се успоставити неколико нивоа формализама везаних за квантне генераторе са акцентом на оне у оптичком делу спектра. Описи најнижим нивоом, који укључује еквивалентне шеме, могу се проширити и на друге еквиваленције физичких проблематика, које се решавају развијеним програмима у електротехници. Шеме су на нивоу макроскопских, али и дефинисаних еквивалентних величина на микроскопском (атомском-електронском нивоу). Размотриће се кинетичке једначине са једноставнијим прилазом, али и поједностављене ласерске једначине на квантно-семи квантном прилазу. Применом одговарајућих трансформација, *Fourier*-ове анализе, добија се пет главних ласерских једначина, које пружају основу за многе режиме рада квантних генератора и појачивача (режими: слободне генерације, *Q switch*, синхронизације, са филтром, двомодни систем, са губицима, итд.). Овде треба да се укључе теорије стабилности типа Љапунова, итд.

За неке од изабраних типова квантних генератора анализираће се аналитичко моделовање и резултати програмских пакета посвећених ласерима, као и системи пумпани електронским (релативистичким) сноповима и ставови нуклеарне физике, који се морају укључити на почетку, по успоравању до термалних енергија, како би могли да се примене потребни делови теорије кондензованог − чврстог стања и ласерске технике.

Постојећи рачунарски програми дају могућност брзог моделовања и приказа расподеле енергије, температуре, модова и сл., у активном материјалу и резонатору. За специјалне геометрије, извршиће се моделовање и добити расподела температуре у активном материјалу, за време рада одабраног ласерског режима. Поредиће се разне геометрије пумпања. Савремени ласери са најкраћим постојећим импулсима захтевају нове формализме. Области нелинеарне оптике и квантне електродинамике, *Glauber*-ова стања и сл. су области које морају да буду укључене. Два главна формализма, термодинамички и квантно-механички са вероватноћама прелаза, уз методе пертурбације и секундарног квантовања су природно морали да буду допуњени, ако се генералније обухватају типови *Brillouin*-ов, *Raman*-ов, *Compton*-ов, солитон, фибер ласер и други.

**Кључне ријечи**: квантни генератори, формализми, динамика, моделовање, ласер.