Passive Q-Switching of Solar Laser Cavities Using a GaAS Semiconductor Crystal

Shaimov Fayzullo Fatullayevich
Tashkent State Agrarian University, fayzi2008@mail.ru

Fayziev Shakhobiddin Shavkatovich
Bukhara State University, fayziyev_83@mail.ru

Abstract

The results of numerical experiments on the use of a gallium arsenide semiconductor crystal as a Q-switching element and, at the same time, an output mirror in solar laser cavities are presented. The results of mathematical modeling show that at optimal concentrations of (antistructural) defects in a gallium arsenide crystal, a sequence of short pulses can be obtained.

Keywords: *solar laser, Q-switching, gallium arsenide, pulse.*

I. INTRODUCTION

The effective use of laser technology in various fields, such as experimental research in the natural sciences, thermonuclear fusion, materials processing technologies, digital and information technologies, medicine, the military, and agriculture opens up many promising opportunities. For example, in the oil and gas industry, lasers are used to clean asphalt-paraffin deposits formed on the inner walls of tubing, laser scanning is used to monitor oil tanks [1], and laser welding, surfacing and cutting are also used [2].

II. Literature review

The authors of [3] listed the following areas of application for the use of lasers in agriculture:

1. The use of laser technologies in mechanical engineering and repair agricultural machinery.

2. The use of laser information technology to analyze the quality of agricultural products, express diagnostics of the state of plants and fruits, atmosphere, soil, etc.

3. Laser agro- and biotechnologies.

Of course, such a wide-scale use of laser technology in different areas requires lasers with different radiation parameters. Based on this, we can conclude that the study of the improvement of laser technologies is an urgent task.

For a long time, intensive work has been carried out on the creation of solar-pumped lasers. For example, the creation of solar-pumped solid-state lasers was reported in [4–6], and the authors of [7, 8] proposed several schemes of solar-pumped gas lasers, although their efficiency is relatively low (0.2-0.3%) [8]. The authors of [9] showed for the first time the possibility of creating a space-based liquid pulsed laser.

III. Analysis

In many papers devoted to solar pumping lasers, generation has been studied. Little has been studied about the possibility of generating a solar laser with Q-switching of the resonator, there is no information on the use of semiconductor saturating absorbers, for example, a GaAs crystal on the resonators of such lasers.

Gates based on saturable absorbers are of particular interest because such gates provide the simplest method of Q-switching. In these semiconductors, the centers of saturating absorption are defect levels in the band gap of the semiconductor. In particular, the absorption spectrum of a GaAs semiconductor crystal has a peak, the maximum of which coincides with the energy (~1.2 eV) of photons emitted by lasers with neodymium-containing active substances. It is associated with an (intrinsic) defect level of the EL2 type in the band gap of the crystal.

In this work, a model of a solar laser pumped at the focus of a large solar furnace (LSF) was developed; phosphorus oxychloride activated by neodymium ions (POCl3-SnCl4-Nd3+) was chosen as the active medium. Such an active medium has a relatively low absorption coefficient (2-3·10-4 см-1) at a generation wavelength of 1.05 μm, with a neodymium concentration of 1020 cm-3 [9]. And the possibility of using a gallium arsenide crystal, simultaneously, as a passive element and as an output mirror, in the resonator of a solar laser is being considered.

For clarity, we first consider the free operating mode of a solar laser and then examine the Q-switched generation mode, which is carried out using a gallium arsenide crystal as an output mirror.

Model of a liquid laser with free generation. As is known, in the focus of the LSF, on an area of 1m2, the maximum power is ~1 MW. At the same time, using computer control of heliostats, it is not difficult to obtain a uniform distribution of the solar flux in the focal spot, which corresponds to an intensity of 100 W/cm2. A row of glass cylindrical cells 100 cm long with an inner diameter of 1.5 cm can be installed in the focal spot. Secondary rectangular concentrators with a width 2–3 times greater than the cell diameter can be used to efficiently concentrate solar radiation. In this case, about 25 cuvettes can be placed at the focus.

Calculations were carried out for an active element of phosphorus oxychloride with neodymium (POCl3-SnCl4-Nd3+) pumped by the solar flux at the focus of the LSF, the maximum power of the concentrated solar radiation flux for each cell was assumed to be 40 kW.

The resonator length is 1m, the reflection coefficient of the output mirror is R2=0.95. In the calculations of the solar laser model, the following values were used parameters of phosphoryl chloride: concentration of neodymium ions NNd=1020 cm-3, forced transition cross section from the 4F3/2 state to the 4I11/2 state σ=8*10-20 см2, lifetime of the upper laser level τ_2=2,5*10-4 c, refractive index of the laser medium n=1.46, absorption coefficient μ=3*10-4 см-1.

In a liquid neodymium-containing active medium based on phosphorus oxychloride, the active centers are neodymium ions, on which generation occurs according to the well-known four-level scheme. Since the lifetime in states, 1 and 3 is short compared to the lifetime in state 2 (τ _1 ≈ τ _3 ≈ 10-9 c , while τ _2 ≈ 10-4 c), lasing can be described by the rate equations [10]:

$$\frac{dN_2}{dt} = W(t)N_g - BqN_2 - \frac{N_2}{\tau_2} \quad (1.1)$$

$$\frac{dq}{dt} = V_a BqN_2 - \frac{q}{\tau_a} \quad (1.2)$$

$$N_{Nd} = N_g + N_2 \quad (1.3)$$

$$N_1 = N_3 = 0 \quad (1.4)$$

N_1, N_2, N_3 – concentrations of neodymium ions in excited states 1, 2 and 3 (cm-3). Ng is the concentration of neodymium ions in the ground state (cm-3), NNd is the concentration of neodymium ions in the laser liquid (cm-3), W(t) is the specific pumping rate; B is the Einstein coefficient of stimulated emission;

q is the total number of photons in the resonator; τ_2 is the average lifetime in the excited state 2 (s); Va is the volume occupied by the mode in the active medium (cm3); τ_a is the average lifetime of a photon in the resonator (s). The following initial conditions N2(0) = 0 and q(0) = q0 were used in the calculations, where q0 is a small number of photons in the resonator necessary for generation to occur.

The following expression was chosen for the specific pumping rate [10]:

$$W = \delta P/(Vh\upsilon N_g); \quad (2)$$

where, δ - is the pumping efficiency; P - the pump power (Вт); V - the volume of the laser liquid (см3); hν = 1.17 эВ – the laser transition energy.

For the values B and τ_a, the following expression was used [10]:

$$B = \sigma l c_0/V_a L' = \sigma c_0/V \quad (3)$$

$$\tau_a = L'/\gamma c_0 \quad (4)$$

where, V - the effective volume of the resonator mode (см3).

The following expression for V was used in the calculations [10]:

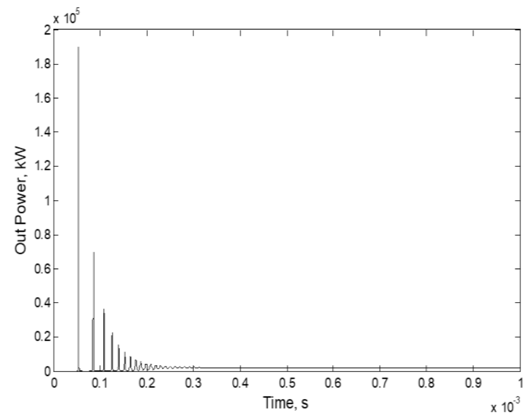
$$V = (1/4)\pi\omega_0^2 L' \quad (5)$$

If q(t) is known, then it is easy to calculate the output power radiated through one of the two resonator mirrors. The output power was determined by the following expression [9]:

$$P_1 = (\gamma_1 c_0/2L')\hbar\omega q \quad (6)$$

There is no analytical solution to system (1), and to describe the system's transition to the lasing regime, to determine the time dependence of the lasing power and energy at a given pump rate and various parameters of the laser system, it was solved by the Adams numerical method.

Pic.1. Time dependence of the output power Pout of a liquid laser when pumped from the sun.



The time dependence of the output power of a liquid laser with the same parameters, operating in the free-running mode, when pumped from the Sun, is shown in Fig.1. It can be seen that at first the laser operates in a spiked mode, and after 300 μs it switches to a stationary mode of operation. In the free-running mode, the radiation power is about 2250 W.

IV. Discussion

Liquid Solar Laser Model with Semiconductor Output mirror.

In this model, it is assumed that in the solar laser cavity, instead of the output mirror is equipped with a saturating semiconductor gallium arsenide crystal. With such a resonator scheme, the GaAs crystal simultaneously performs the function of an output mirror and a saturating absorber; subsequently, the laser begins to operate in a Q-switched mode.

It is known that two-photon absorption associated with interband transitions, one-photon absorption at impurity levels, and also absorption on free carriers, which are formed due to one- and two-photon absorptions, are possible in a GaAs crystal. Let us write the basic equations describing the above processes using the GaAs energy level scheme and taking into account the relaxation times [11]:

$$\frac{\partial N^+}{\partial t} = \frac{\sigma_n I(N-N^+)}{h\nu} - \frac{\sigma_p I N^+}{h\nu} - \frac{N^+}{\tau_1} \quad (7.1)$$

$$\frac{\partial p}{\partial t} = \frac{\beta I^2}{2h\nu} + \frac{\sigma_p I N^+}{h\nu} - \frac{p}{\tau_2} \quad (7.2)$$

$$\frac{\partial n}{\partial t} = \frac{\beta I^2}{2h\nu} + \frac{\sigma_n I(N-N^+)}{h\nu} - \frac{n}{\tau_2} \quad (7.3)$$

where, N – the density of neutral impurity levels (cм-3), N+ - the density ionized impurity levels (cм-3), n– the concentration of free electrons, p- the concentration of holes (cм-3), σ_p - the cross section for electron transition from the valence band to the impurity level (cм2), σ_n - the cross section for electron transition from the impurity level to the band conductivity (cм2), τ1– the N+ level lifetime (s), τ2 – the recombination time of free carriers (s), I – the radiation intensity (W/cм2), hv- the radiation energy (eV), β- the two-photon absorption coefficient (cм·W-1).

In the first approximation, we can take τ 2≈ τ 1 ≈ τ ≈ 1 ns for GaAs, since τ 2 is mainly determined by the concentration of defect levels. The intensity equation can be written as [11]:

$$dI/dz = -\propto I - \beta I^2 - n\sigma_{fc} I \quad (8)$$

where, $\alpha = \sigma_n(\mathrm{N} - \mathrm{N}^+) + \sigma_p N^+$ - the single-photon absorption coefficient, σ_{fc} - the absorption cross section on free carriers.

To get the expression for the transmittance, we solve equation (8) under the assumption that after passing the distance z in the GaAs crystal, the pulse parameters change insignificantly:

$$I(t) = I_0(t)\frac{\exp[-(\propto + n\sigma_{fc})z]}{1+[\beta I_0(t)/(\alpha+n\sigma_{fc})]\{1-\exp[-(\alpha+n\sigma_{fc})z]\}} \quad (9)$$

From expression (9) we obtain for transmission in a GaAs crystal:

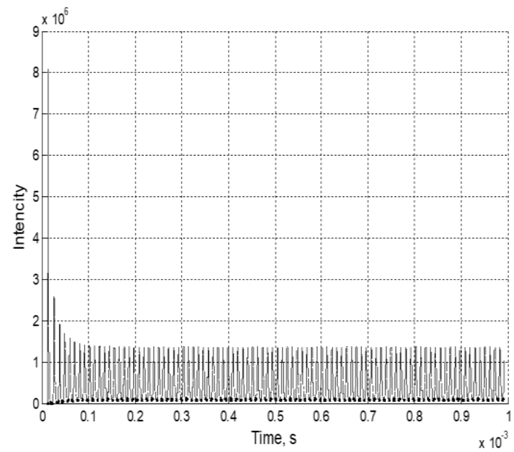
$$T = \frac{exp[-(\propto + n\sigma_{fc})z]}{1+[\beta I_0(t)/(\alpha+n\sigma_{fc})]\{1-exp[-(\alpha+n\sigma_{fc})z]\}} \quad (10)$$

that, $z = d/cos\theta$; d– the crystal thickness; θ- the angle between the normal to the surface of the crystal and the direction of radiation inside it.

The following parameters are used in the model: β =30 cм/ГВт, σ_n =10^{-16} cм^2, $\sigma_p = \sigma_n/10$, $\sigma_{fc} = 6 * 10^{-18}$ cм^2.

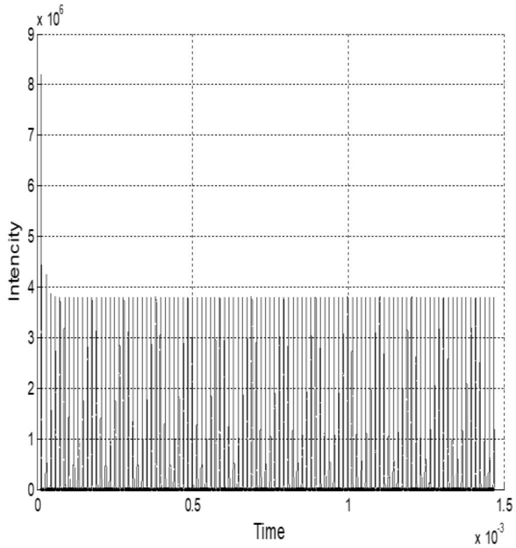
Here we use a method based on systematic tracking of the evolution of the pulse in the plane-wave approximation and in the traveling coordinate system for each pass through the individual elements of the resonator, taking into account the corresponding transmittance for the intensity, starting from a relatively long and weak noise pulse of spontaneous emission.

Pic.2. Time dependence of the output radiation at a defect concentration of 2·1016 cm-3 on a GaAs crystal. Pumping power 40000 W



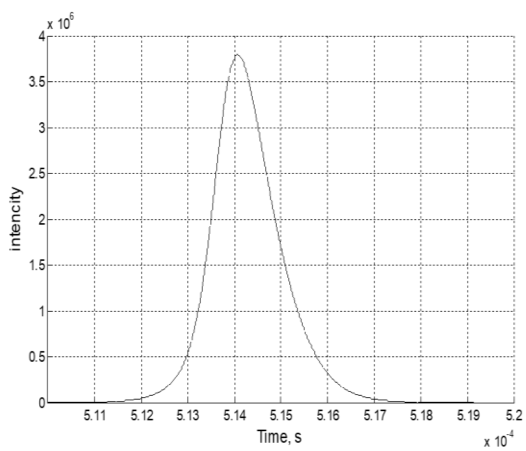
In Pic.2. the time dependence of the output radiation at a concentration defects 2·1016 cm-3 in the GaAs crystal. As can be seen from the figure, the generation begins with the formation of a sequence of pulses, which decay with time, and the laser switches to a stationary mode of operation. Starting with a defect concentration of 3.5·1016 cm-3 into a stationary pulse-periodic mode of operation, where a continuous sequence of pulses is generated (pic. 3).

Pic.3. Time dependence of the output radiation at a defect concentration of 3.5*1016 on a GaAs crystal. Pumping power 40000 W



In Pic.4. one expanded pulse from this sequence of pulses is shown (Pic. 3). It can be seen that the average pulse duration is approximately 1.5 μs.

Pic.4. Pulse shape at a pump power of 40000 W



V. Conclusion

The results of numerical experiments show that the use of a GaAs crystal in solar-pumped lasers as an output mirror makes it possible to obtain sequences of stable pulses of short duration at optimal values of the defect concentration. It can be assumed that such a laser with high-intensity intracavity radiation can switch to the mode-locked generation mode.

References

1. Kotelnikov S.I. Application of laser scanning technology for monitoring of oil tanks// Mine surveying bulletin. No. 2. pp. 1-5.2016.

2. Grezev A., V. Grezev et al. “Development of laser technologies for the oil and gas industry” // Stankoinstrument. No. 2. pp. 38-41, 2016.

3. Budagovsky A.V., Budagovskaya O.N. Photonics in agriculture and nature management, promising areas of development // Information Bulletin of the Laser Association. No. 15-16. pp. 1-8. 2016.

4. Hwang, I.H. and Lee, J. H., 1991. Efficiency and Threshold Pump Intensity of CW Solar-Pumped Solid-State Lasers // IEEE Journal of Quantum Electronics, Vol. 27. N. 9.2129–2134.

5. Brauch U., Muckennschnabel, J., Opower, H. and Wittwer, W. , 1991, Solar-pumped Solid State Lasers for Space to Space Power Transmission” // Space Power, Resources, Manufacturing and Development. Vol. 10. N 3-4.pp. 285-294.

6. Brauch U., Muckennschnabel, J., Thomson, G. A., Bernstein, H., Yogev, A., Reich, A. and Oron, M., 1992. Influence of Operating Temperature on the Power, Divergence, and Stress-Induced Birefringence in Solar-Pumped Solid State Lasers // Optical Engineering, Vol.31. no. 5. 1072-1078.

7. Golger A.L., Gudzenko L.I., Yakovlenko

S.I. On the direct conversion of the solar energy into laser radiation // Quantum Electronics, 5. P.1982. 1978.

8. Gordiets B.F., Panchenko V.Y. Gas lasers with solar excitation // Uspekhi Fizicheskikh Nauk. No. 149.pp. 551. 1986.

9. Seregin A.A., Seregina A.E. Liquid pulsed laser model space-based with solar pumping // Quantum electronics. T 34. No. 2. S. 99. 2004.

10. Zvelto O. Principles of lasers. - Moscow: "Mir". 1990. P.560.

11. S. A. Bakhramov and Sh. D. Paiziev, "Formation of defects in a GaAs crystal under the action of picosecond laser radiation near the optical damage threshold," Opt. 2006. V. 100. No. 3. pp. 451 - 453.