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Model of a pulsed liquid solar-pumped spaceborne laser

A.A. Seregin, E.A. Seregina

***Abstract*. A model of a pulsed liquid solar-pumped laser is constructed. A neodymium-containing phosphorus oxychloride ($POCl_3 - SnCl_4 - Nd^{3+}$) liquid is proposed as an active medium. The lasing parameters of this medium are calculated for a spaceborne laser as functions of its size and the coefficient of solar energy concentration.**

Keywords: *liquid laser, neodymium, phosphorus oxychloride, solar pump, nearest space.*

1. Introduction

The first solar-pumped lasers were developed right after the advent of conventional lasers [1 – 3]. Although these crystal lasers had low output powers ($\sim 1 - 3$ W), the outlook for the use of the solar pump was pointed out at once. Thus, NASA (USA) announced the development of a spaceborne laser with a focusing mirror of diameter $\sim$ 300 m collecting $\sim$ 100 MW of the solar radiation power [4]. The authors of paper [5] believe that solar-pumped lasers (solar lasers) open up a new promising field in energetics (photoenergetics).

However, because of a low power density of solar radiation in the nearest space ($\sim$ 1 kW m^{-2}) and at the sea level ($\sim$ 0.7 kW m^{-2}) and the necessity to use focusing mirrors, an efficient solar laser has not been built so far despite a number of interesting proposals [5 – 12]. The maximum output laser power of 18 W has been obtained to date by pumping a neodymium-doped yttrium-aluminium crystal of volume 0.94 cm^3 [6].

Difficulties encountered in the preparation of active solid media of large volumes and in their uniform pumping, as well as low long-term optical and thermal strength of crystals and glasses can substantially restrict a further increase in the output power of such lasers. Fibre lasers appear to be more promising for the development of a solar solid-state laser [7, 8]. Unfortunately, no experimental studies of such lasers were reported so far.

Along with solar solid-state lasers, a few types of solar gas lasers have been proposed [5, 9, 10]. The analysis of their possibilities performed in review [10] showed that gas lasers are not promising for practical applications because their efficiency is low (0.2 % – 0.3 %), they should have a large size and require a high energy concentration. Despite this conclusion, at present the researchers in Arzamas-16 are developing within the framework of the ISTC project a 10-W solar photodissociation laser. They also assume to elaborate recommendations for the development of a technological solar laser emitting up to 100 kW [11].

Except already conventional solar lasers mentioned above, a heterostructure solar laser was proposed in theoretical paper [12]. Although no experimental investigation of such lasers were reported so far, such a laser will have a high threshold, as pointed out in Ref. [12], and will require a very high concentration coefficient of the solar energy ($\sim 10^4$) and a very complicated cooling system.

In this paper, we consider for the first time a model of a pulsed liquid solar laser using a neodymium-containing phosphorus oxychloride ($POCl_3 - SnCl_4 - Nd^{3+}$) liquid as an active medium. The use of a liquid active medium offers a number of substantial advantages. First, an active element with any geometrical dimensions can be made; second, the laser cooling is simplified; third, liquid lasers can produce high output powers; for example, almost 6 J of the output pulse energy was obtained from 1 cm^3 of this active medium [13]. The fourth advantage of these lasers is low cost of the active medium. And finally, a new technology was developed for synthesis of the above-mentioned liquid, which provides a very low absorption coefficient at the laser wavelength.

2. Choice of the laser design and active medium

A solar laser of the simplest design consists of a highly reflecting cylindrical parabolic mirror turned to the Sun. A glass cell of length l with the inner diameter r filled with an active medium is placed in the focus of the mirror parallel to its axis. One of the ends of the cell is a highly reflecting mirror and another is a translucent mirror (to couple out radiation). Because the beams reflected from the cylindrical parabolic mirror pass through the focal line, such a design provides the maximum utilisation of solar radiation to pump the active medium.

As mentioned in Introduction, we propose to use as an active medium a neodymium-containing phosphorus oxychloride liquid, which is already widely used in liquid lasers [14]. Certain advances achieved at present in the preparation of this laser liquid allow one to use it as an active medium for a solar-pumped laser. In particular, the absorption

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coefficient of the liquid at the 1.052-μm laser wavelength was significantly reduced without deteriorating its basic parameters. While the absorption coefficient was, as a rule, $(2-3)\times10^{-3}$ cm^{-1} at the concentration of neodymium ions equal to 10^{20} cm^{-3}, at present the liquid was synthesised with the absorption coefficient equal to $(2-3)\times10^{-4}$ cm^{-1}, which significantly reduces the lasing threshold and improves the output parameters of the laser.

3. Model of a solar-pumped liquid laser

Lasing of neodymium ions in a neodymium-containing phosphorus oxychloride liquid occurs according to the well-known four-level scheme. Because the lifetime of states 1 and 3 is short compared to that of state 2 ($\tau_1 \approx \tau_3 \approx 10^{-9}$ s, whereas $\tau_2 \approx 10^{-4}$ s), lasing can be described by simplified rate equations [15]

$$\begin{aligned} \frac{\mathrm{d}N_2}{\mathrm{d}t} &= W(t)N_{\mathrm{g}} - BqN_2 - \frac{N_2}{\tau_2}, \\ \frac{\mathrm{d}q}{\mathrm{d}t} &= \left(\upsilon BN_2 - \frac{1}{\tau_{\mathrm{a}}}\right)q, \\ N_{\mathrm{Nd}} &= N_{\mathrm{g}} + N_2, \\ N_1 &= N_3 = 0 \end{aligned} \tag{1}$$

with the initial conditions $N_2(0) = 0$ and $q(0) = q_0$, where q_0 is a small number of photons in the resonator required for the development of lasing; N_1, N_2, and N_3 are the concentrations of neodymium ions in excited states 1, 2, and 3; N_{g} is the ground-state concentration of neodymium ions; N_{Nd} is the concentration of neodymium ions in the laser liquid; $W(t)$ is the specific pump rate; B is the Einstein coefficient for stimulated emission; q is the total number of photons in the resonator; τ_2 is the average lifetime of excited state 2; υ is the mode volume in the active medium; and τ_{a} is the average lifetime of a photon in the resonator.

The specific rate of solar pumping can be written in the form [15]

$$W(t) = \begin{cases} \delta P/(Vh\nu N_{\mathrm{g}}) & \text{for } 0 \leqslant t \leqslant \tau_{\mathrm{p}}, \\ 0 & \text{for } t < 0 \text{ and } t > \tau_{\mathrm{p}}, \end{cases} \tag{2}$$

where τ_{p} is the pump pulse duration; δ is the pump efficiency; P is the solar pump power; V is the laser liquid volume; and $h\nu = 1.17$ eV is the laser transition energy.

To find the pump power and efficiency, we consider the solar spectral pump power density Φ per square metre in the wavelength range 0.4 – 1.0 μm of interest to us, which is shown in Fig. 1 [16]. Solar radiation at shorter wavelengths should be suppressed with the help of an appropriate optical filter because this radiation is strongly absorbed by a matrix, resulting in its undesirable heating. By integrating over the above wavelength range, we can represent the solar pump power corresponding to the solar radiation flux of area S collected in the nearest space in the form

$$P = S\int \Phi(\lambda)\mathrm{d}\lambda = 950S, \tag{3}$$

where S is measured in square metres and P in watts.

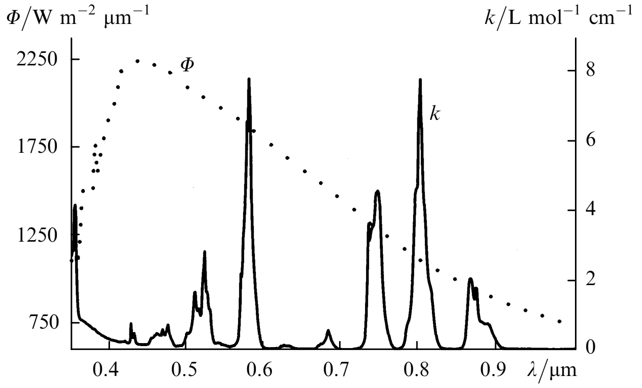

Figure 1. Wavelength dependences of the spectral power density Φ of solar radiation and the absorption coefficient k of the $POCl_3-SnCl_4-Nd^{3+}$ laser liquid.

Figure 1 also shows the dependence of the absorption coefficient of the $POCl_3 - SnCl_4 - Nd^{3+}$ laser liquid on the incident radiation wavelength. One can see that the absorption bands of neodymium ions are completely overlapped by the solar radiation spectrum, which gives promise that a solar liquid laser can be developed.

Because the system of equations (1) has no analytic solution, we solved it numerically by the Gear method using the DGEAR subroutine from the IMSL library to describe the lasing development and to find the laser output power and energy for the specified dependence of the pump rate on time and various parameters of the laser.

4. Results and analysis of calculations

The system of equations (1) was solved for the phosphorus oxychloride liquid for the following values of its basic parameters: the concentration of neodymium ions $N_{\mathrm{Nd}} = 10^{20}$ cm^{-3}, the cross section for the stimulated $^4F_{3/2} - {}^4I_{11/2}$ transition $\sigma = 8\times10^{-20}$ cm^2, the lifetime of the upper laser level $\tau_2 = 2.5\times10^{-4}$ s, the refractive index of the laser medium $n = 1.46$, the absorption coefficient $\mu = 3\times10^{-4}$ cm^{-1}, and the resonator length is equal to the cell length l. The coefficient of solar-energy concentration ξ was defined as the ratio of the area S of the captured solar energy flux to the area $2\pi rl$ of the inner surface of the cell, where r is the inner radius of the cell. We assumed in our calculations that ξ cannot exceed 1000 because this value was considered in many papers as the maximum value achievable in experiments. One of the laser mirrors was assumed highly reflecting, while the transmission of another mirror was optimised for each cell length l. The optimum transmission coefficients T for the output mirror proved to be equal to 0.1, 0.25, and 0.3 for the resonator lengths equal to 50, 100, and 200 cm, respectively.

It is most difficult to calculate the pump efficiency δ, which is a product of the efficiency η_{a} of absorption of the sunlight by the quantum yield η_{pq} of emission and the reflection efficiency of a focusing mirror [15]. To estimate the pump efficiency, we first calculate the efficiency of absorption of the sun light propagating through a $POCl_3 - SnCl_4 - Nd^{3+}$ liquid layer of thickness $2r$ for the concentration of neodymium ions indicated above. The quantity η_{a} is defined by the expression

$$\eta_{\mathrm{a}} = \frac{\int \Phi(\lambda)[1 - \exp(-2k(\lambda)r]\mathrm{d}\lambda}{\int \Phi(\lambda)\mathrm{d}\lambda}, \qquad (4)$$

where the integration limits are 0.4 and 1.0 μm. For $2r = 1.5$ cm, we found that $\eta_{\mathrm{a}} = 0.134$. Another quantity, which is directly related to the pump efficiency, is the quantum yield η_{pq}, whose value for the $\mathrm{POCl_3-SnCl_4-Nd^{3+}}$ liquid pumped by a xenon flashlamp is 0.9 – 0.95. Assuming that the reflection efficiency of a focusing mirror is 0.8 (which is quite real for a polished aluminium mirror), we obtain the solar pump efficiency for the upper laser level of neodymium ions in the active element of diameter 1.5 cm equal to 0.1.

As for the pump pulse duration, our calculations showed that it could be 1 ms or even longer, if the laser is cooled efficiently. We assumed that the pump pulse duration was $\tau_{\mathrm{p}} = 10^{-3}$ s.

The specific threshold energy of the laser depends on the length l of the active element and was 8.8×10^{-4}, 7.8×10^{-4} and 7.1×10^{-4} J cm^{-3} for the active element of length 50, 100, and 200 cm, respectively. The rest of calculation results are presented in Figs 2 – 4. Figure 2 shows the typical time dependence of the upper laser-level population for a solar-pumped pulsed liquid laser. One can see that the laser first operates in the quasi-stationary mode and passes already after 150 μs to the stationary mode.

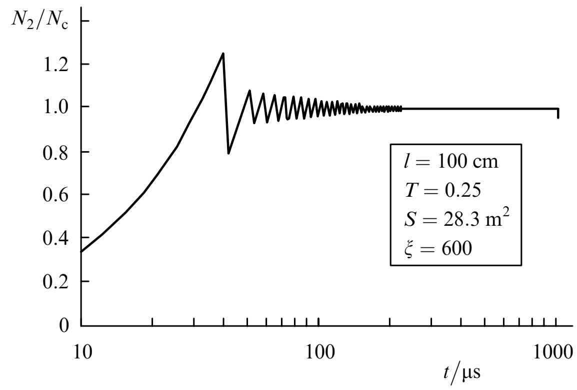

Figure 2. Time dependence of the upper-level population in the active medium of a liquid laser pumped by a 1-ms solar radiation pulse; N_{C} is the critical population value.

Figure 3 shows the time dependence of the output power of a solar-pumped free-running pulses liquid laser with the same parameters. The laser operates in the spike mode for the first 150 μs and then passes to the stationary mode. The peak power of the individual spikes achieves a few tens of kilowatts, but the average output pulse power is 1.03 kW.

Figure 4 shows the dependences of the output energy and average output power of the solar-pumped pulsed liquid laser on the coefficient of solar-energy concentration for different lengths of the active element. One can see that both these quantities increase with increasing the active-element length and the coefficient of solar-energy concentration. In this case, the same output energy can be obtained either by increasing the active-element length or the coefficient of solar-energy concentration.

The efficiency of a solar-pumped liquid laser, which is defined as the ratio of the laser output energy to the energy obtained from the Sun, increases from 2.8 % to 3.6 % depending on the coefficient of energy concentration and weakly depends on the active-element length.

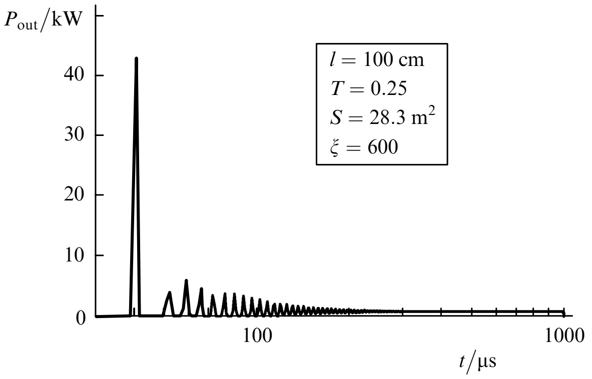

Figure 3. Time dependence of the output power P_{out} of a liquid laser pumped by a 1-ms solar radiation pulse.

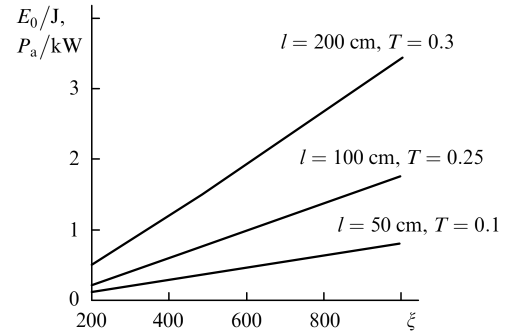

Figure 4. Dependences of the output pulse energy E_0 and average output pulse power P_{a} of the solar-pumped liquid laser on the coefficient ξ of solar energy concentration for different lengths l of the active element and different transmission coefficients T of the output mirror.

Note finally that the laser liquid is heated due to nonradiative transitions. Our calculations showed that the temperature of the liquid active elements of length 50, 100, and 200 cm in the case of a 1-ms pulse and the coefficient of energy concentration equal to 10^3 will increase by 0.16, 0.32, and 0.67 K, respectively.

5. Conclusions

We have proposed to use the neodymium-containing phosphorus oxychloride liquid to build a solar-pumped pulsed liquid spaceborne laser. Our calculations have shown that such a laser can be developed within the framework of technological and design solutions achieved at present. Thus, flowing-liquid pulsed lasers operating with a pulse repetition rate of 10 Hz both in the free-running mode [17] and single-pulse mode [18] have been already built. Also, a liquid pulsed laser emitting 2500-μs pulses has been developed [19].

Note finally that phosphorus oxychloride doped with neodymium can be also used for the development of a terrestrial solar-pumped pulsed laser. At present we are completing calculations of such a laser, and the results will be published in near future.

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