THE PERSPECTIVITY OF THE SEMICONDUCTOR GLASSES, AS THE ACTIVE MEDIUM FOR THE MINIATURE LASER

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The threshold of generation at the longitudinal and transversal methods of pumping and output power at the multimode and one mode regimes for the miniature lasers have been calculated. The probability of miniature laser creation on the base of the sulfide, oxy-sulfide and sulfide- oxygen glasses, activated by Nd^{3+} at the longitudinal and transversal excitation methods, has been created.

The high-qualitative optical fibers, used in the communication systems, have the minimal losses in the wave length region 1mcm-1.3mcm. It is followed, that miniature neodymium lasers, generating the radiations on the wave lengths ~1.06mcm, can be successfully applied in these systems, as the light source. For the clearing of the perspectivity of sulfide, oxy-sulfide and sulfide-oxygen glasses, as the miniature laser medium, it is need to compare the dependence of threshold on the nonresonance losses at the different pumping configurations and also the dependence of the output power on the input one for these glasses with the corresponding dependences for the glasses by the type ED-2 [1].

As it is known, the laser generation condition has the form:

$$r_1 r_2 e^{2l(\gamma_l-\delta)} = 1, \tag{1}$$

where r_1 and r_2 are mirror reflection coefficients, γ_l is the medium gain exponent, l is the medium length, δ are losses in the medium. Taking into consideration, that $\gamma_l=\sigma\cdot\Delta N$, where ΔN is the population inversion between Stark sublevels of the generation transition, σ is the cross-section of this transition. Taking into consideration (1), we have:

$$\Delta N = \frac{1}{2\sigma}\left(2\delta + \frac{1}{l}Ln\frac{1}{r_1 r_2}\right). \tag{2}$$

If photon number, falling on the unit area of laser medium in the unit time is I_0, then the photon number, absorbed on the unit area in the unit time will be $I_0(1-e^{-\alpha_p l})$. Here α_p is the medium absorption coefficient.

In the continuous regime of laser work:

$$I_0(1-e^{-\alpha_p l}) = \frac{l\Delta N}{F_\alpha \tau_f}, \tag{3}$$

where τ_f is the life time of the upper laser level, F_α is the particle part in the Stark sublevel of the upper laser level, from which the laser transition takes place:

$$F_\alpha = \frac{e^{-\frac{\Delta E}{kT}}}{1+e^{-\frac{\Delta E}{kT}}} \quad \text{or} \quad \frac{1}{1+e^{-\frac{\Delta E}{kT}}},$$

where ΔE is the energy gap between Stark sublevels of the upper laser level ${}^4F_{3/2}$. The first expression for F_α corresponds to the case, when laser transition takes place from the upper sublevel ${}^4F_{3/2}$ and the second expression corresponds to the case, when transition takes place from the lower sublevel.

From the formula (3), we define the I_0

$$I_0 = \frac{l\Delta N}{\tau_f(1-e^{-\alpha_p l})F_\alpha} \tag{4}$$

Substituting the formula (2) in the formula (4), we obtain:

$$I_0 = \frac{(2l\delta + Ln\frac{1}{r_1 r_2})}{2\sigma\tau_f(1-e^{-\alpha_p l})F_\alpha} \tag{5}$$

Let's write $2l\delta + Ln\frac{1}{r_1 r_2}$ in the form:

$$2l\delta + Ln\frac{1}{r_1 r_2} = \Gamma_0 + \Gamma_R,$$

where Γ_0 is the nonresonance losses, but Γ_R is the resonance ones $\Gamma_R=2l\sigma N\beta_l/z$, where N is the work ion density, $\beta_t = e^{-\frac{\Delta E\, {}^4I_{11/2},{}^4I_{9/2}}{kT}}$, Z is the ratio of summary population of Stark sublevels ${}^4I_{9/2}$ and sublevels ${}^4I_{11/2}$ till the lower laser sublevel to the population of the lowest Stark sublevel ${}^4I_{9/2}$. Expressing the formula (5) in the energies, we define the power density at the threshold:

$$P_{treshold} = h\nu_p I_0 = \frac{hc(\Gamma_0+\Gamma_R)}{2\lambda_p\sigma\tau_f F_\alpha(1-e^{-\alpha_p l})} \tag{6}$$

In the case of transversal pumping we have:

$$P_{treshold} = \frac{hc(\Gamma_0+\Gamma_R)}{2\lambda_p\sigma\tau_f F_\alpha \alpha_p l}. \tag{7}$$

Let's consider the 4-level energy laser circuit. The time change of the stored atom energy N on the upper laser level and the energy E_f of coherent electromagnetic field inside the resonator is described by the equations:

$$\frac{dN}{dt} = R - A_n - A(N-n) - \beta E_F(N-n)$$

, (8)

$$\frac{dE_F}{dt} = \beta E_F(N - n) - E_F(T + \varepsilon)$$

where t is time, N is the atom quantity in the upper laser level, but n is the atom quantity in the lower laser level. The both values N and n are multiplied on the energy of laser transfer. R is the atom quantity, pumped in the upper laser level in the unit time. The parameter of the stimulated radiation $\beta = \frac{C\sigma}{SLh\nu_L}$, where $h\nu_L$ is the laser transition energy, S is the laser medium cross-section, L is the length of the one transfer in the resonator, T is the omission of the output mirror, divided on the $\frac{2L}{C}$, ε are losses in two transfers, in the resonator, divided on the $\frac{2L}{C}$, A is equal to the inverse life time of the upper laser level. The ε parameter is the damping coefficient of the resonator, excepting the losses, caused by the output mirror and any resonance losses. The Bolzman population of lower laser level, namely, the resonance losses (Γ_R) have been taken into consideration by us. In the formula (8) the derivations on t are equal to zero in the continuous laser regime:

$$0 = R - A_n - A(N-n) - \beta E_F(N-n)$$

(9)

$$0 = \beta E_F(N - n) - E_F(T + \varepsilon)$$

The output power is defined as TE_f. Calculating (9) in respect of E_F, we obtain:

$$P = T\left(\frac{R - A_n}{T + \varepsilon} - \frac{A}{\beta}\right). \qquad (10)$$

From the extremum condition $\frac{dP}{dT} = 0$, we find the maximum output power in the continuous regime:

$$T_0 = \varepsilon\left(\sqrt{\varphi} - 1\right)$$

, (11)

$$P_0 = (R - An)\left(1 - \frac{1}{\sqrt{\phi}}\right)^2$$

where $\phi = \frac{\beta(R - An)}{A\varepsilon}$. Thus, ϕ parameter is defined as the ratio of the effective pumping to the minimal effective pumping, needed for the achieving of threshold (at $T=0$). The R parameter is equal to $P_{input}\left(\frac{\nu_L}{\nu_p}\right)$, where P_{input} is pumping power, of absorbed laser medium ν_p is pumping center frequency. Taking into consideration, that resonance losses $\Gamma_R = 2l\sigma\frac{n}{h\nu_L Sl} = \frac{2\sigma n}{h\nu_L S}$, and total loss $\Gamma = \Gamma_0 + \Gamma_R = \frac{c}{2L}\varepsilon + \Gamma_R$, instead of the formulae (11), we obtain:

$$P_{output} = \left(\frac{\nu_L}{\nu_p}\right)\left(P_{input} - \frac{\Gamma_R}{\Gamma}P^1{}_{treshold}\right)\left(1 - \frac{1}{\sqrt{\phi}}\right)^2, \qquad (12)$$

$\phi = \frac{P_{input} - \frac{\Gamma_R}{\Gamma}P^1{}_{treshold}}{\left(1 - \frac{\Gamma_R}{\Gamma}\right)P^1_{treshold}}$ and $P^1_{treshold} = P_{treshold} \cdot S$ is absorbed power at the threshold.

Multiplying the right part of the formula (12) on the f, we obtain the output in the multimode regime at the longitudinal pumping

$$P_{output} = f\left(\frac{\nu_L}{\nu_p}\right)\left(P_{input} - \frac{\Gamma_R}{\Gamma}P^1_{treshold}\right)\left(1 - \frac{1}{\sqrt{\phi}}\right)^2. \qquad (13)$$

The f is defined as the ratio of the volume, engaged by the in the active medium to the pumped volume.

Instead of the step function, in limits of which, the transversal distribution of the intensity stays constant, we take Gaussian distribution function, which is character for TEM_{100} mode:

$$E_F = E_{F_c} e^{-\frac{2\rho^2}{\omega^2}}, \qquad (14)$$

where E_{F_c} is light energy on the surface unit along resonator axis, ρ is the distance from the resonator axis, ω is gudgeon radius.

The density of the light energy and the density of the inversion energy are described by the equations:

$$\int \frac{dE_F}{dt}dS = \int\left[\beta E_F(N - n) - E_F(T + \varepsilon)\right]dS \qquad (15)$$

$$\frac{dN}{dt} = R - A_n - A(N-n) - \beta E_F(N-n). \qquad (16)$$

Here, it is proposed, that values E_F, N and R are beforehand integrated on the length of laser medium. Here N and n are atom quantities in the surface unit in the upper and lower levels correspondingly, and parameter of the stimulated radiation β is equal to $\frac{c\sigma}{Lh\nu_L}$. R is the atom quantity, pumped in the upper laser bed, on the surface unit in the time unit and is equal to $P_{input}\left(\frac{\nu_L}{\nu_p}\right)\Big/S$ The dS is the surface element in the plane, which is perpendicular to resonator axis. In the stationary case instead of the equations (15) and (16), we obtain:

$$\int E_F dS = \frac{\beta}{T+\varepsilon}\int E_F(N-n)dS \qquad (17)$$

$$R - A_n = A(N-n) + \beta E_F(N-n) \qquad (18)$$

Substituting the formula (18) in the formula (17), we obtain:

$$\int E_F dS = \frac{\beta(R-An)}{T+\varepsilon}\int\frac{E_F dS}{A+\beta E_F} \qquad (19)$$

Substituting the expression for E_F of formula (14) in the both parts of the equation (19), after integration, we obtain:

$$E_{F_c} = \frac{(R-An)}{T+\varepsilon} Ln\left(1+\frac{\beta E_{Fc}}{A}\right) \qquad (20)$$

The laser output is defined by the following expression:

$$P_{output} = T\int E_F dS \quad . \qquad (21)$$

Substituting the formula (14), we obtain:

$$P_{output} = \frac{\pi\omega^2}{2} T E_{F_c} \,. \qquad (22)$$

Substituting the E_{F_c} value, defined in the formulae (22), in the formula (20), we obtain:

$$P_{output} = \frac{\pi\omega^2(R-An)T}{2(T+\varepsilon)} Ln\left(1+\frac{2\beta P_{output}}{\pi\omega^2 AT}\right) \,. \qquad (23)$$

At the optimal omission of mirror and the maximum output the $\frac{dP_{output}}{d\left(\frac{1}{T}\right)} = 0$ takes place. Differentiating the both parts of the formula (23), relatively $\frac{1}{T}$ and taking into consideration $\frac{dP_{output}}{d\left(\frac{1}{T}\right)} = 0$, we obtain:

$$P^0_{output} = \frac{T^0(\phi-1)}{\varepsilon\phi}(R-An)\frac{\pi\omega^2}{2}\,, \qquad (24)$$

where $\phi = \frac{(R-An)\beta}{A}$ and upper indexes on P^0_{output} and T^0 correspond to maximum and optimal values correspondingly. Substituting the P^0_{output} (24) in the right part of the formula (23), we obtain:

$$P_{output} = \frac{\pi\omega^2(R-An)T^0}{2(T^0+\varepsilon)} Ln\phi \,. \qquad (25)$$

Using the expression T^0, found in the formula (24), we obtain:

$$P_{output} = \frac{\pi w^2}{2}(R-An)(Ln\phi - \frac{\phi-1}{\phi})\,, \qquad (26)$$

Using for expressions for R, threshold and loss, we obtain:

$$P^0_{output} = \frac{\omega^2}{2\omega_0^2}\left(P_{input} - \frac{\Gamma_R}{\Gamma}P^1_{treshold}\right)\left(Ln\phi - \frac{\phi-1}{\phi}\right), \qquad (27)$$

where ω_0 is radius of the active medium.

Using the expressions of the formulae (6), (7), (13) and the spectroscopy data (table 1), the comparisons of the generated parameters of glasses in the corresponding parameters of ED-2, in which the generation has been obtained, were carried by us.

Table 1.

Spectroscopy data of glasses

Material	λ_L, nm	λ_p, nm	α_p, cm^{-1}	σ, Cm^2	τ, Mcc	N, cm^{-3}	F_α	β_x (10^4)	$\frac{1}{z}$	Γ_R, (%)
$0.112Nd_2S_3\,0.888La_2S_3\text{-}3Ga_2S_3$	1073,2	12	22,6	$4{,}7\cdot10^{-20}$	45	$5\cdot10^{20}$	0,74	1,05	0,505	0,011
$0.095Nd_2S_3\,0.905La_2S_3\text{-}2.3Ga_2S_3$	1073,2	812	18,4	$3{,}8\cdot10^{-20}$	62	$5{,}3\cdot10^{20}$	0,75	1	0,444	0,0097
$0.097Nd_2S_3\,0.903La_2S_3 3Ga_2O_3$	1067,4	809	14,8	$2{,}5\cdot10^{-20}$	88	$6{,}08\cdot10^{20}$	0,76	1	0,457	0,0094
$0.085Nd_2S_3\,0.915La_2S_3\,2.3Ga_2O_3$	1071,2	810	15	$2{,}9\cdot10^{-}$	82	$6{,}2\cdot10^{20}$	0,75	1,05	0,449	0,011

				20						
$La_2S_3 \cdot 2Ga_2O_3$ – 3.8% Nd^{3+}	1071,2	810	20,8	$2{,}9 \cdot 10^{-20}$	51	$7{,}6 \cdot 10^{-20}$	0,75	1	0,48	0,01
$0.11Nd_2O_2S \cdot 0.89La_2O_2S \cdot 3Ga_2S_3$	1071	812	16,9	$3{,}2 \cdot 10^{-20}$	65	$5{,}2 \cdot 10^{20}$	0,73	1,1	0,442	0,009
ED-2	1060	808	1,27	$2{,}9 \cdot 10^{-20}$	300	$2{,}83 \cdot 10^{20}$	0,64			0,064

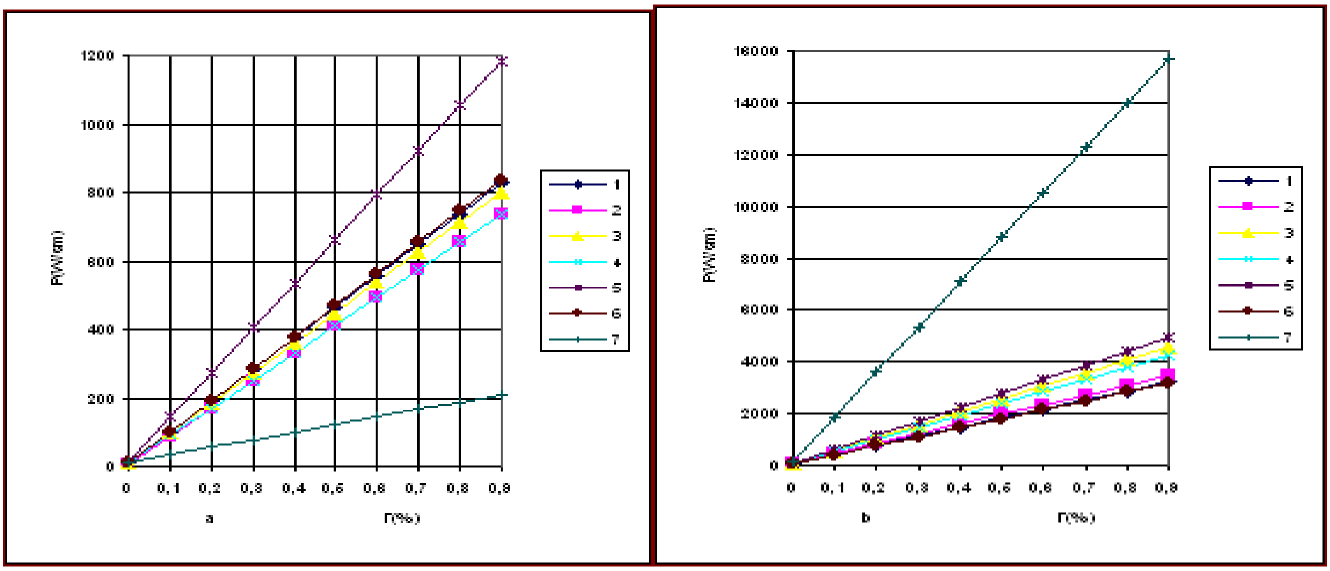

Fig.1. The dependence of the density of threshold power of pumping on the nonresonance losses at the (a) longitudinal and (b) transversal pumpings:
1- $0.112Nd_2S_3 \cdot 0.888La_2S_3 \cdot 3Ga_2S_3$
2- $0.095Nd_2S_3 \cdot 0.905La_2S_3 \cdot 2.3Ga_2S_3$
3- $0.097Nd_2S_3 \cdot 0.903La_2S_3 \cdot 3Ga_2O_3$
4- $0.085Nd_2S_3 \cdot 0.915La_2S_3 \cdot 2.3Ga_2O_3$
5- $La_2S_3 \cdot 2Ga_2O_3$ – 3.8% Nd^{3+}
6- $0.11Nd_2O_2S \cdot 0.89La_2O_2S \cdot 3Ga_2S_3$
7- ED-2.

The dependence of the threshold on the nonresonance losses for every material at the transversal pumping is presented on the fig.1b. The length of every material l=1cm. For the calculation of Z parameter, we propose, that Stark sublevels $^4I_{9/2}$ are on the equal distances in the energy scale. According to F_α parameter, the gaps between Stark components $^4F_{3/2}$ for every glass on absorption spectrums $^4I_{9/2} \rightarrow {}^4F_{3/2}$, fixed at T=77K, were defined by us. From the fig.1b, it is seen, that investigated by us glasses have the very low threshold in the comparison with ED-2 at the longitudinal pumping. Thus, investigated by us glasses are the perspective materials for the creation of miniature lasers at the transversal pumping. It is need to note, that formulae (13) and (26) have to be multiplied on the gathering of diode radiation coefficient ξ and the efficiency of diode η. These coefficients don't take into consideration by us for simplicity. The dependence of the threshold on the nonresonance losses for every material at the longitudinal pumping is presented on the fig.1c. The length of every material was considered as optimized one, i.e. $\ell = \frac{1}{\alpha_p}$. It is seen, that the generation thresholds are significantly higher, than ED-2 in the investigated glass by us. The relative small thresholds have the glasses with the compositions $0.095Nd_2S_3 \cdot 0.905La_2S_3 \cdot 2.3Ga_2S_3$ and $0.085Nd_2S_3 \cdot 0.905La_2S_3 \cdot 2.3Ga_2O_3$.

The dependence of the output power on the input one on the longitudinal pumping in the multimode is represented on the fig.2.

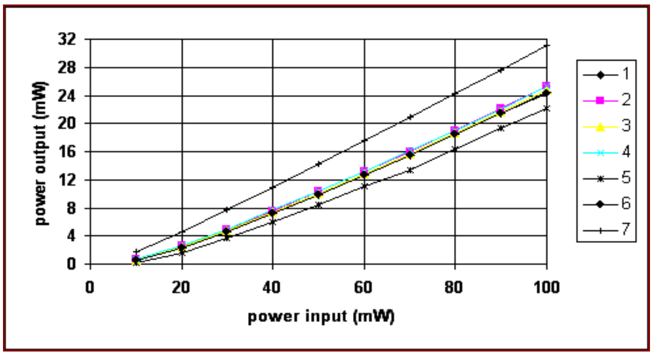

Fig.2. The dependence of the output power on the input one at the longitudinal pumping in the multimode regime:
1- $0.112Nd_2S_3 \cdot 0.888La_2S_3 \cdot 3Ga_2S_3$
2- $0.095Nd_2S_3 \cdot 0.905La_2S_3 \cdot 2.3Ga_2S_3$
3- $0.085Nd_2S_3 \cdot 0.915La_2S_3 \cdot 2.3Ga_2O_3$
4- $0.097Nd_2S_3 \cdot 0.903La_2S_3 \cdot 3Ga_2O_3$
5- $La_2S_3 \cdot 2Ga_2O_3$ – 3.8% Nd^{3+}
6- $0.11Nd_2O_2S \cdot 0.89La_2O_2S \cdot 3Ga_2S_3$
7- ED-2.

For these calculations, it is proposed, that nonresonance losses are equal to 0.15%, f=0,5, the operating radius of the laser element is ~60mcm for every material and ω=0,5ω_0. It is seen, that investigated by us glasses have the significant worse generation parameters, than ED-2 at the longitudinal pumping.

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[1] *Yariv*. Kvantovaya elektronoka, M.: “Sovetskoye radio”, 1980. (in Russian).

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YARIMKEÇİRİCİ ŞÜŞƏLƏRDƏN MİNİATÜR LAZERLƏRİN AKTİV ELEMENTLƏRİ KİMİ İSTİFADƏ ETMƏK İMKANLARI BARƏDƏ

Miniatür lazerlər üçün eninə və uzununa həyacanlanma hallarında, çıxış gücü və lazer generasiyası başlayan güc bir və çox moda hallarında hesablanmışdır. Nd^{3+} aktivləşmiş sulfid, oksosulfid və sulfidoksid şüşələrinin əsasında uzununa və eninə həyacanlanma hallarında miniatür lazerlər yaratmaq imkanları araşdırılmışdır.

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О ПЕРСПЕКТИВНОСТИ ПОЛУПРОВОДНИКОВЫХ СТЕКОЛ, КАК АКТИВНОЙ СРЕДЫ МИНИАТЮРНОГО ЛАЗЕРА

Вычислены порог генерации при продольных и поперечных способах накачки и выходная мощность при многомодовых и при одномодовых режимах для миниатюрных лазеров. Выяснена возможность создания миниатюрных лазеров на основе сульфидных, оксосульфидных и сульфидооксидных стекол активированных Nd^{3+} при продольных и поперечных способах возбуждения.

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