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Continuous wave lasing at 1.54 μm in a flashlamp-pumped yttebium – erbium-doped glass

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***Abstract*. Continuous wave lasing is obtained for the first time in a flashlamp-pumped ytterbium – erbium-doped glass.**

Keywords: *ytterbium – erbium-doped phosphate glass, erbium laser, cw lasing.*

1. Introduction

Although erbium glasses are attractive because they produce lasing at the eye-safe wavelength, they have not aroused for a long time interest among the developers of lasers due to their low lasing efficiency. The situation changed once it was shown that the lasing efficiency of erbium glasses can be drastically increased by doping them with additional sensitisers – trivalent chromium ions [1, 2]. Later, the efficiency of flashlamp-pumped erbium lasers was enhanced up to 4.5 % [3]. However, all this concerns pulsed lasers. As for cw lasing, it was achieved only quite recently due to the development of selective pump sources – semiconductor In – Ga – As diodes. As a result, a number of erbium glass lasers was developed at present, both flashlamp- and diode-pumped, which can operate in a single-pulse and cw regimes, with output pulse energies from tens of microjoules to tens of joules. In addition, the *Q*-switching regime is also possible.

The aim of this paper is to demonstrate that flashlamp-pumped erbium glass is also capable of cw lasing.

Among many active media known at present only neodymium-doped yttrium aluminium garnet crystals are of practical interest for the development of flashlamp-pumped cw lasers. The attempt to obtain cw lasing in a neodymium-doped phosphate glass has failed because of a low mechanical strength of the glass, whereas cw lasing achieved in a neodymium-doped silicate glass has a very low efficiency (0.02 % – 0.1 %) [4].

A substantial positive factor justifying the attempt to obtain cw lasing in a erbium glass is the long lifetime of the metastable $^4I_{13/2}$ level of erbium ions, which exceeds 8 ms. However, the three-level scheme of lasing along with the low thermal conductivity and mechanical strength of the glass compared to those of crystals can negate this advantage. Therefore, it is difficult to expect the achievement of good energy parameters for cw erbium glass lasers and cw lasers based on other glasses.

2. Laser medium and the active element

It was necessary to determine first of all the optimal concentrations of ytterbium and erbium doping ions. Co-doping with chromium ions was completely excluded in this case because only 60 % of the power absorbed by chromium ions is transferred to erbium ions, while the remaining part is spent to heat the active element. In addition, because of a large Stokes shift (the absorption maximum of Cr^{3+} is located at 0.66 μm, while lasing occurs at 1.54 μm), an additional efficient source of hear release appears.

As for the concentration of ytterbium ions, it should be chosen as high as possible both to increase the absorption of flashlamp radiation and to enhance the absorbed energy transfer from ytterbium to erbium ions. It was shown earlier [5] that for the $(0-0.1)N_{\mathrm{Er}}$ inversions typical of cw lasing, the efficiency of energy transfer from ytterbium to erbium was maximal when the concentration of ytterbium ions was 2×10^{21} cm^{-3} and almost did not change up to the maximum concentration 4×10^{21} cm^{-3} that can be achieved in a phosphate glass, whereas in the energy accumulation regime during *Q*-switching, for the $(0.5-0.8)N_{\mathrm{Er}}$ inversion, the optimal concentration of ytterbium ions was $(2-2.5)\times10^{21}$ cm^{-3}. In our case, the factors restricting the concentration of ytterbium ions by the value 2.2×10^{21} cm^{-3} are: (i) the technology of the glass synthesis (at a high concentration of ytterbium ions, crystallisation of the glass occurs); (ii) the desire to restrict the thermooptical constant W by the value $(30-40)\times10^{7}$ K^{-1}; and (iii) the preservation of the maximum thermal conductivity of phosphate glasses $\lambda_{\mathrm{h}}=0.7-0.8$ W m^{-1}K^{-1}.

The latter two parameters are extremely important for obtaining cw lasing. The parameter W determines the difference δp of the optical paths for the pints of the cross section where temperatures differ by δT according to a simple relation

$$\delta p = LW\delta T, \qquad (1)$$

where L is the active element length. Therefore, a strong thermal lens will be formed in glasses with a large value of

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W, which prevents the achievement of cw lasing. The thermal conductivity determines the temperature drop between the active element centre and its side surface. The temperature drop is described in the stationary regime by the expression

$$\delta T_{\mathrm{st}} = \frac{qr^2}{4\lambda_{\mathrm{h}}}, \qquad (2)$$

where q is the power of thermal release in the unit volume and r is the active element radius.

The thermal conductivity λ_{h}, which determines δT, thereby also affects the thermal lens effect. However, the influence of λ_{h} on the mechanical strength of the active element is even more substantial. Because the temperature drop produces mechanical stresses in the active element, which cause the destruction of the active element above the glass stress threshold, it is necessary to have the maximum possible value of λ_{h}.

The search for the optimal glass composition satisfying the requirements discussed above is an extremely complicated problem, and the necessity to dope an erbium glass with no less than 20 % (weight) of ytterbium oxide further restricts the choice. As a result, we chose the glass composition oxides of alkali metals and aluminium with technological additions. Because our aim was to obtain cw lasing, we paid the main attention to the mechanical strength of the glass that would provide the achievement the lasing threshold without the active element damage. The calculated parameters of the glass in the mixture were $\lambda_{\mathrm{h}} = 0.75$ W m^{-1} K^{-1}, $W = 40 \times 10^{-7}$ K^{-1}, and the linear coefficient of thermal expansion $\alpha = 80 \times 10^{-7}$ K^{-1}.

By solving numerically the system of kinetic equations, we found the dependence of the threshold pump power absorbed by the active element of diameter 2.7 mm on the concentration of erbium ions (Fig. 1). The calculation was performed for the pump wavelength of 0.976 μm coinciding with the maximum of the only absorption band of ytterbium (the absorption bands of erbium ions at their working concentration no more than 10^{19} cm^{-3} are so weak that they can be safely neglected). We used in calculations the active element length equal to 80 mm in accordance with the size of the available INP-3/75 flashlamp illuminator. The lasing threshold was determined at the instant of the achievement of the gain $k_{\mathrm{th}} = 0.0045$ cm^{-1}, which is determined by the resonator losses $k_{\rho} = \ln(1/R_{\mathrm{out}})/(2L)$ [here R_{out} is the reflectivity of the output mirror equal to 96 %, $L = 75$ mm (illuminated region)] and by the inactive losses k_{n} in the non-illuminated regions of the active element near its ends. We assumed that the pump radiation was uniformly absorbed over the diameter and length of the active element.

One can see from Fig. 1 that the minimum absorbed threshold pump power is 76 W at the concentration of erbium ions equal to $(0.3-0.5)\times10^{19}$ cm^{-3}. Based on these data, we founded the glass by adding erbium ions at a concentration of 0.4×10^{19} cm^{-3}.

3. Experiment

We used an illuminator of the 'dense packing' type representing a silvered quartz tube of diameter 10 mm with the symmetrically positioned active element and flashlamp within it. This construction was fixed within a metal housing and was cooled with running distilled water containing bichromate. The circulation rate of water was 3 L min^{-1}. We used an INP-3/75 pulsed xenon lamp for pumping because the emission spectrum of arc krypton lamps (lines in the region from 750 to 900 nm) employed for pumping neodymium lasers does not overlap with the absorption spectrum of ytterbium ions lying between 900 and 1000 nm. The active element of length 80 mm was mechanically rounded to a diameter of 4 mm and then its diameter was reduced by chemical etching down to 2.7 mm, except the parts of the element of length 5 mm adjacent to its ends. The length of the resonator formed by a plane output mirror with the reflectivity 96 % and an interchangeable highly reflecting mirror was 22 cm.

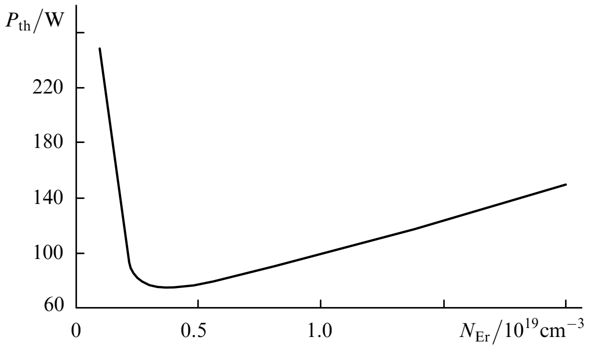

Figure 1. Calculated dependence of the threshold pump power P_{th} on the concentration N_{Er} of erbium ions for the ∅2.7×80 mm active element and $R_{\mathrm{out}} = 96$ %.

As mentioned above, a thermal lens is produced in the active element due to its heating upon pumping. In the stationary regime upon uniform pumping, an axially symmetric temperature distribution is established in the active element. This results, according to (1), in the appearance of an astigmatism-free spherical lens in the active element. Therefore, it is reasonable to attempt to compensate for the curvature of the laser resonator using a convex mirror with the appropriate radius of curvature.

For this purpose, we placed by turn a plane mirror and convex spherical mirrors with radii of curvature of 2 and 1 m as a highly reflecting mirror. In the case of two first mirrors, we failed to obtain lasing. Figure 2 shows the results obtained with a convex highly reflecting mirror with the radius of curvature of 1 m. The radiation divergence was 10 mrad for the flashlamp current equal to 12.5 A. The diameter of the laser beam on the output mirror was ~ 1 mm.

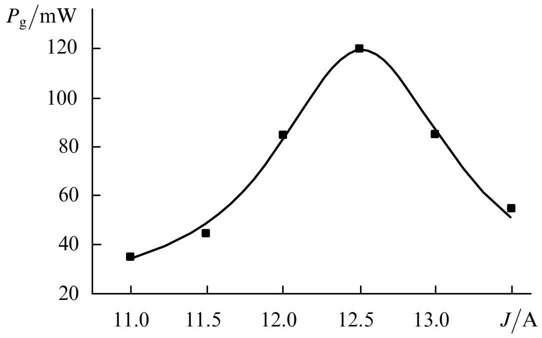

Figure 2. Experimental dependence of the laser output power P_{out} on the flashlamp current J.

The threshold pump power P_{th} was ~ 1050 W for the flashlamp voltage of ~ 100 V. The coefficient η_{p} of conversion of the electric pump power to the optical power absorbed by the active element calculated by dividing the calculated optical power (Fig. 1) by the real threshold power is 7.2 %.

Unfortunately, the experimental conditions were far from perfect and we failed to obtain results of interest for practical applications. First, because of a small distance between the active element and flashlamp in the 'dense packing' type illuminator, the active element is heated inhomogeneously over its cross section. This leads, along with the photoelastic effect produced by mechanical stresses, to astigmatism and aberrations, which cannot be corrected with the help of a convex spherical mirror. For this reason, lasing occurs only in a small central part of the active element of diameter 1 mm. Second, the stability region of the resonator proved to be narrow. Therefore, the achievement of the 120-mW output should be considered only as the first demonstration of cw lasing.

It is interesting to estimate the maximum lasing efficiency η_{las} and output power that could be obtained in this active element in the absence of resonator losses caused by thermooptical distortions.

The expression for the lasing efficiency of the erbium active medium can be obtained from the known relation [6] supplemented with the coefficient η_{s} characterising the efficiency of energy transfer from ytterbium to erbium ions

$$\eta_{\text{las}} = \frac{P_{\text{g}}}{P_{\text{p}}} = \left(1 - \frac{P_{\text{th}}}{P_{\text{p}}}\right)\eta_{\text{p}}\eta_{\text{st}}\eta_{\text{s}}k_{\rho}k_{\text{th}}, \qquad (3)$$

where $\eta_{\text{st}} = 0.976/1.54 = 0.63$ is the coefficient describing the Stokes loss and $\eta_{\text{s}} = 0.6$ for the threshold inversion. For the pump power $P_{\text{p}} = 1800$ W, which was achieved in our experiments without the active-element damage, we obtain from (3) $\eta_{\text{las}} = 0.67\,\%$ and the output power $P_{\text{out}} = 12$ W. We assumed that the pump radiation absorbed by the active element is distributed uniformly over its cross section and lasing occurs within the entire volume of the active element.

4. Conclusions

We have demonstrated for the first time cw lasing in an erbium glass. Our estimates have shown that a ⌀2.7 × 80 mm active element made of an erbium-doped phosphate glass can provide the output power up to 12 W. However, to achieve such a high output power, it is necessary to solve an extremely challenging problem of the improvement of thermooptical properties of the erbium glass.

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