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# Tunable 2-μm lasing in calcium–niobium–gallium garnet crystals doped with $Ho^{3+}$ ions

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*Abstract.* **Lasing on the $^5I_7 \to {}^5I_8$ transition of $Ho^{3+}$ ions in holmium-doped calcium–niobium–gallium garnet crystals is obtained at a wavelength of about 2095 nm with an output power of 2.1 W under pumping by a laser based on Tm:$LiYF_4$ crystal. Tunable lasing in these crystals within a wavelength range of 2045–2120 nm is achieved using an interference–polarisation filter.**

***Keywords:*** *crystals with garnet structure, $Ho^{3+}$ ions, lasing.*

## 1. Introduction

Calcium–niobium–gallium garnet (CNGG) and calcium–lithium–niobium-gallium garnet (CLNGG) crystals belong to crystals with disordered crystal structure. These crystals were synthesised for the first time more than thirty years ago [1]. They are characterised by a lower melting temperature (1430–1470 °C) than yttrium–aluminium garnet (YAG), gadolinium–scandium–aluminium garnet (GSAG) and gadolinium–scandium–gallium garnet (GSGG) crystals. This simplifies the growth of CNGG and CLNGG crystals and allows one to synthesise them by technologies that do not use iridium.

Due to the disordered crystal structure of CNGG and CLNGG, the absorption and luminescence spectra of rare-earth (RE) ions in these crystals are inhomogeneously broadened. This is of interest for developing tunable and mode-locked lasers based on CNGG and CLNGG crystals doped with RE ions.

At present, there exist extensive experimental data on the spectral-luminescent and laser properties of CNGG and CLNGG crystals doped with $Nd^{3+}$, $Tm^{3+}$, and $Yb^{3+}$+ ions [2–14]. Some results of investigation of the spectroscopic characteristics of $Ho^{3+}$:CNGG crystals are presented in [15]. However, we failed to find works on the laser properties of these crystals resonantly pumped to the $^5I_7$ level of $Ho^{3+}$ ions in the available literature.

The aim of the present work is to study the laser characteristics of Ho:CNGG crystals under resonant pumping by a Tm:$LiYF_4$ laser to the $^5I_7$ level of $Ho^{3+}$ ions.

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## 2. Experimental samples and methods

The calcium–niobium–gallium garnet crystals doped with $Ho^{3+}$ ions [Ho:$Ca_3(NbGa)_5O_{12}$] were grown by the Czochralski methods in a platinum crucible. The concentration of $Ho^{3+}$ ions in the grown crystals was 0.7 at %. To perform spectral-luminescent measurements, we cut plane-parallel plates 7.5 mm thick from the grown CNGG crystals. In laser experiments, we used a cylindrical active element 18 mm long and 4 mm in diameter.

The absorption spectra were recorded on a Lambda 950 PerkinElmer spectrophotometer. A halogen lamp was used as a radiation source. As a detector for measuring the absorption spectra at the $^5I_8 \to {}^5I_7$ transition of $Ho^{3+}$ ions, we used a PbS photodetector. The luminescence spectra at this transition were measured using an MDR-23 monochromator. For excitation we used a solid-state MGL-F-532nm-2W laser based on Nd:$YVO_4$ crystal with a wavelength of 532 nm. The luminescence signal was recorded by a PbS photoresistor.

The laser spectrum was measured using a Horiba HR 1000 spectrometer and a PbS photodetector.

## 3. Experimental results

To achieve lasing on the $^5I_7 \to {}^5I_8$ transition under resonant pumping to the $^5I_7$ level of $Ho^{3+}$ ions, one must know the spectral-luminescent characteristics of the $^5I_8 \to {}^5I_7$ and $^5I_7 \to {}^5I_8$ optical transitions of $Ho^{3+}$ ions in the corresponding crystal matrix. The absorption spectrum on the $^5I_8 \to {}^5I_7$ transitions of $Ho^{3+}$ ions in the active element at $T = 300$ K is shown in Fig. 1.

The wavelength dependence of the stimulated emission cross section $\sigma_{em}(\lambda)$ for the $^5I_7 \to {}^5I_8$ transition of $Ho^{3+}$ ions in a Ho:CNGG crystal ($C_{Ho} = 0.7$ at %) was determined by the Füchtbauer–Ladenburg formula [16]

$$\sigma_{em}(\lambda) = \frac{\lambda^5 \beta_{JJ'} I_{em}(\lambda)}{8\pi c n^2 \tau_{rad} \int I_{em}(\lambda)\lambda d\lambda}, \quad (1)$$

where $\tau_{rad}$ is the radiative lifetime of the $^5I_7$ level of $Ho^{3+}$ ions; $n$ is the refractive index of the medium; $I_{em}(\lambda)$ is the relative luminescence intensity; $c$ is the speed of light; $\beta_{JJ'}$ is the luminescence branching ratio; and $\lambda$ is the wavelength. For the $^5I_7 \to {}^5I_8$ transition, $\beta_{JJ'} = 1$. The lifetime $\tau_{rad}$ was determined as the reciprocal probability of the $^5I_7 \to {}^5I_8$ transition of $Ho^{3+}$ ions in Ho:CNGG crystals [17] and was found to be 13 ms.

The wavelength dependences of the absorption and stimulated emission cross sections for the $^5I_8 \to {}^5I_7$ and $^5I_7 \to {}^5I_8$ transitions of $Ho^{3+}$ ions are presented in Fig. 2.

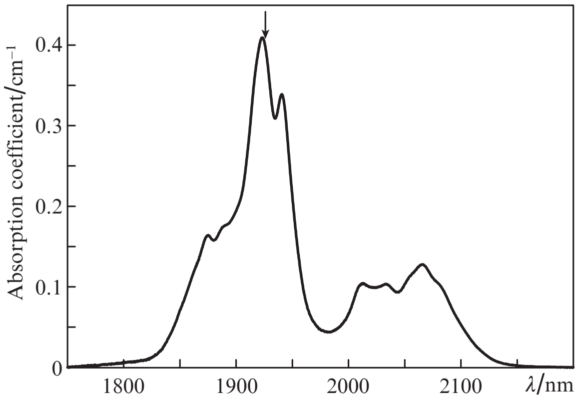


**Figure 1.** Absorption spectrum for the $^5I_8 \rightarrow {}^5I_7$ transition of $Ho^{3+}$ ions in the Ho : CNGG active element ($C_{Ho}$ = 0.7 at %); $T$ = 300 K. The arrow indicates the wavelength of optical pumping into the $^5I_7$ level of $Ho^{3+}$ ions in Ho : CNGG crystals.

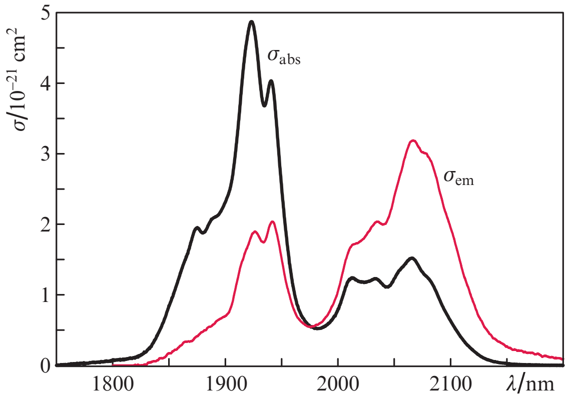


**Figure 2.** Spectral dependences of the absorption and stimulated emission cross sections on the $^5I_8 \rightarrow {}^5I_7$ and $^5I_7 \rightarrow {}^5I_8$ transitions of $Ho^{3+}$ ions; $T$ = 300 K.

Using the found spectral dependences $\sigma_{abs}(\lambda)$ and $\sigma_{em}(\lambda)$, one can determine the spectral profile of the gain for the $^5I_7 \rightarrow {}^5I_8$ laser transition of $Ho^{3+}$ ions in Ho : CNGG crystals as

$$\sigma_g(\lambda) = P\sigma_{em}(\lambda) - (1 - P)\sigma_{abs}(\lambda), \quad (2)$$

where $P$ is the relative inverse population of levels. Figure 3 presents the calculated gain profiles $\sigma_g$ for $P$ = 0.1, 0.2, 0.3. One can see that the gain region at $P$ = 0.3 for Ho : $Ca_3(NbGa)_5O_{12}$ crystals corresponds to the wavelength range of 1970 – 2200 nm.

The absorption spectra of $Ho^{3+}$ ions in Ho : CNGG crystals show that the best wavelength for efficient pumping of the active element is $\lambda_p$ = 1925 nm (see Fig. 1). Because of this, we used a Tm : $LiYF_4$ laser with wavelength $\lambda_p$ = 1925 nm as a pump source. This wavelength was obtained as a result of intracavity selection with the use of an interference – polarisation filter (IPF). The Tm : $LiYF_4$ laser was pumped by two fibre-coupled diode arrays (DAs). The maximum output power of the pump laser was 15 W.

The optical scheme of the solid-state Ho : CNGG laser pumped by a Tm : $LiYF_4$ laser is shown in Fig. 4. The pump beam was focused into a Ho:CNGG active element by lenses L1 and L2 with focal distances of 200 and 100 mm, respectively. The pump beam waist diameter was 160 μm. The

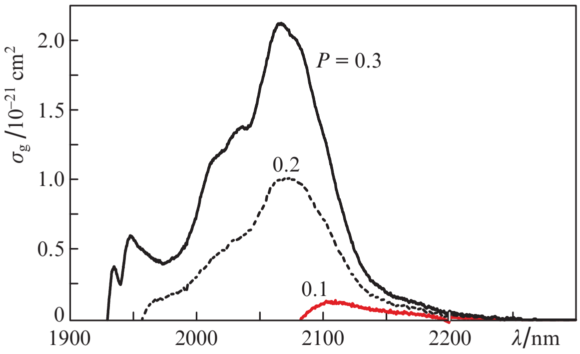


**Figure 3.** Spectral profile of the gain for the $^5I_7 \rightarrow {}^5I_8$ transition of $Ho^{3+}$ ions in Ho : CNGG crystals ($C_{Ho}$ = 0.7 at %) at inverse populations $P$ = 0.1, 0.2, 0.3.

Ho : CNGG laser cavity was formed by a plane input mirror with transmittance $T$ = 90 % at the pump wavelength and reflectance $R$ = 99.8 % at the lasing wavelength. As output mirrors, we used spherical mirrors with curvature radius $r$ = 150 mm and transmittances $T$ = 2.1 %, 3.9 %, and 6.8 % at the lasing wavelength. The maximum power and efficiency of the Ho : CNGG laser was achieved using an output mirror with transmittance $T$ = 6.8 %.

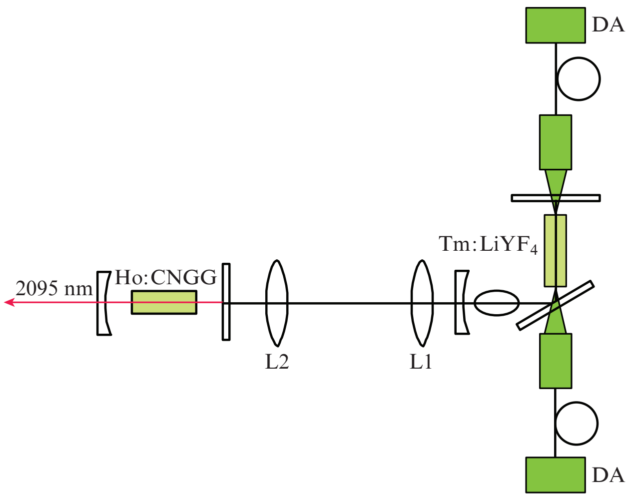


**Figure 4.** Optical scheme of a solid-state Ho : CNGG laser pumped by a Tm : $LiYF_4$ laser.

Figure 5 presents the Ho : CNGG laser spectrum. One can see that the laser operates at a wavelength of about 2095 nm.

Figure 6 shows the dependence of the output Ho : CNGG laser power on the pump power absorbed in the active element in the case of the output mirror with transmittance $T$ = 6.8 %. In this case, the active element absorbed less than 50 % of the incident pump power. The lasing threshold with respect to the absorbed power was $P_{th}$ = 0.7 W. The slope efficiency with respect to the pump power absorbed in the active element was $\eta$ = 37 %. It should be noted that this efficiency was achieved for the active element without antireflection coatings on faces.

Using an interference – polarisation filter (an $Al_2O_3$ plane-parallel plate 4 mm thick), we tuned the wavelength of the

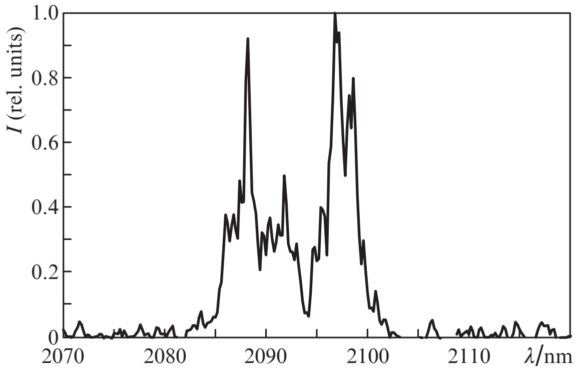


**Figure 5.** Spectrum of the Ho:CNGG laser at a laser power of 1.5 W.

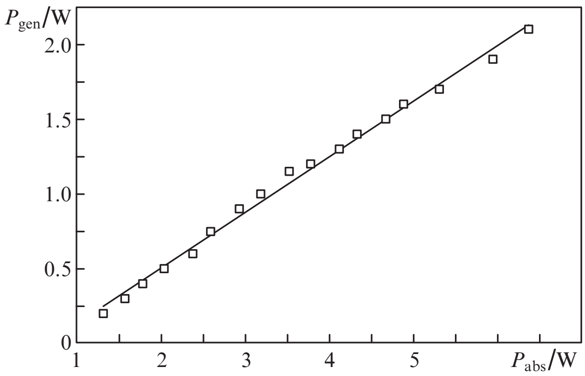


**Figure 6.** Dependence of the Ho:CNGG laser power on the pump power absorbed in the active element.

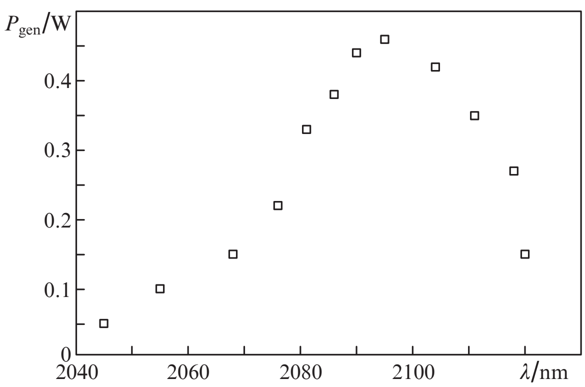


**Figure 7.** Tuning curve of the Ho:CNGG laser at an incident pump power of 8.1 W.

Ho:CNGG laser. It is found that the spectral range of the Ho:CNGG laser operation is 2045–2120 nm (Fig. 7).

## 4. Conclusions

We achieved lasing on the $^5I_7 \rightarrow {}^5I_8$ transition of $Ho^{3+}$ ions in crystals of calcium–niobium–gallium garnet doped with $Ho^{3+}$ ions under pumping by a Tm:$LiYF_4$ laser ($\lambda_p$ = 1925 nm). The Ho:CNGG operated at a wavelength of about 2095 nm with an output power of 2.1 W.

Placing an interference–polarisation filter in the Ho:CNGG laser cavity, we obtained tunable lasing within the wavelength range of 2045–2120 nm, which testifies to the possibility of fabricating an efficient laser emitting in this wavelength range.

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