Optics Communications 301-302 (2013) 84–87

Contents lists available at SciVerse ScienceDirect

Optics Communications

journal homepage: www.elsevier.com/locate/optcom

# $Er^{3+}$ doped GYSGG crystal as a new laser material resistant to ionizing radiation

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ARTICLE INFO

*Article history:*
Received 11 February 2013
Received in revised form
6 March 2013
Accepted 24 March 2013
Available online 16 April 2013

*Keywords:*
Er:GYSGG
Gamma irradiation
Radiation resistance
Efficiency
Mid-infrared

ABSTRACT

We demonstrate a 968 nm diode end-pumped Er:GYSGG ($Gd_{1.17}Y_{1.83}Sc_2Ga_3O_{12}$) laser at 2.796 μm operated in the pulse and continuous-wave (CW) modes. A maximum laser energy of 2.43 mJ is obtained at a pulse width of 2 ms, corresponding to a peak power of 1.25 W and a slope efficiency of 7.2%. In the CW mode, the maximum output power is 348 mW, corresponding to an optical–optical conversion efficiency of 9.2% and a slope efficiency of 10.1%. The $M^2$ factor is 1.94, and the beam divergence is 6.4 mrad. Gamma irradiation at 100 Mrad only slightly affects laser output performance. This result suggests that Er:GYSGG crystal is a potentially new mid-infrared radiation-resistant laser material that can be applied in space and ionizing radiation environment.


## 1. Introduction

Trivalent $Er^{3+}$ $^4I_{11/2} \rightarrow {}^4I_{13/2}$ with 2.7–3 μm laser transitions in various hosts has gained much attention for numerous applications in medical surgery, dentistry, and remote sensing because of the strong water absorption in this wavelength region [1,2]. Moreover, 2.7–3 μm wavebands also suit as a pumping source for 3–19 μm optical parametric oscillator (OPO) laser system [3,4] that can be used for atmosphere detection, environmental protection, military fields, etc. The laser properties of $Er^{3+}$-doped garnet structure crystals, such as Er:$Gd_3Sc_2Ga_3O_{12}$ (Er:GSGG), Er:$Y_3Sc_2Ga_3O_{12}$ (Er:YSGG), and Er:$Y_3Al_5O_{12}$ (Er:YAG), have been subjected to numerous researches because of their good physical characteristics and laser performance [5–9]. To avoid various non-radiative losses and thermal loading, $Er^{3+}$ ions can be pumped directly into the upper laser level $^4I_{11/2}$ by radiation around 970 nm [5]. In this direction, some prominent results have been achieved. Stoneman and Esterowitz [6] obtained a 125 mW laser output at 2.79 μm from Ti:sapphire-pumped Er:GSGG crystal. Dinerman and Moulton [7] reported a 511 mW laser output at 2.79 μm from a 970 nm laser diode (LD)-pumped Er:YSGG crystal. Chen et al. [8] demonstrated a 1.15 W Er:YAG laser output at 2.94 μm with two 964 nm LDs pumping at greater-than-unity quantum efficiency. Unfortunately, the radiation resistance abilities of Er:YAG [10] and Er:YSGG crystals are weak and not suitable for application in an environment of ionizing radiation. Although the GSGG host has strong radiation resistance ability [10], its phonon energy is higher than that of YSGG, leading to longer lifetime of lower laser level $^4I_{13/2}$ (7.5 ms) [11] in comparison to Er:YSGG medium. Recent reports have shown that a new garnet host (GYSGG) can be obtained [12] by replacing a part of $Gd^{3+}$ with $Y^{3+}$ in GSGG. Gao et al. [13] reported that the crystal–field interaction of GYSGG is weaker than those of GSGG and YSAG, which may result in the excellent dual-wavelength laser properties of Nd:GYSGG crystal. Therefore, we combine the merits of GSGG and YSGG and develop a new laser material (Er:GYSGG) to explore a novel 2.7–3 μm laser.

In this paper, we present the results of successful growth of high quality Er:GYSGG crystal by the Czochralski method for the first time. The experimental results on a 968 nm diode end-pumped Er:GYSGG laser operation in the pulse and CW modes are investigated. The absorption spectra and laser properties are also compared before and after 100 Mrad gamma-ray irradiation (the illuminated dose is strong enough for indicating the irradiation effect).

## 2. Experimental setup

Using the Czochralski method, the Er:GYSGG crystal was grown from a melt of congruent composition containing 35 at% $Er^{3+}$. The structural formula can be written as $(Er_{1.05}Gd_{1.17}Y_{0.78})Sc_2Ga_3O_{12}$. The chemicals used initially were $Er_2O_3$ (5 N), $Gd_2O_3$ (5 N), $Y_2O_3$ (5 N), $Sc_2O_3$ (4.5 N), and $Ga_2O_3$ (4.5 N) powders, with an extra 2 wt%

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http://dx.doi.org/10.1016/j.optcom.2013.03.048

$Ga_2O_3$ to compensate for Ga loss due to evaporation. The crystal was allowed to grow in a JGD-60 furnace (Chongqing, China) at a rotation speed of 7 rpm and a pulling rate of 1 mm/h. A high optical quality Er:GYSGG crystal with a dimension of approximately $\Phi$ 25 mm × 100 mm was obtained. A photograph of the as-grown Er:GYSGG laser crystal is shown in Fig. 1. Sample discs were perpendicularly cut from the post-annealing crystals to the growth direction ⟨111⟩ and then polished on both sides. For spectral measurements, samples 2 mm thick were used. For laser experiments, samples 2 mm × 2 mm × 5 mm in dimension were used. The samples were irradiated by $^{60}C_o$ gamma-ray sources at a dose of approximately 100 Mrad and room temperature. Values of induced difference spectrum due to the irradiation were calculated using the formula [14]

$$\Delta K = \ln(T_1/T_2)/d$$

where $d$ is the sample thickness; and $T_1$ and $T_2$ are the crystal transmissions before and after irradiation influence, respectively. The absorption spectra were recorded on a PE lambda 950 spectrophotometer. A modified fluorescence spectrometer (Edinburgh FLSP 920) with an excitation source of 968 nm LD was used to measure the fluorescence spectra and the fluorescence decay curves excited by OPO (opolette 355 I) laser.

A schematic of the laser setup is shown in Fig. 2. The pump source was an InGaAs laser diode that can emit up to 40 W around 968 nm in the pulse and CW modes. The pump beam waist diameter in the crystal was approximated to be 100 μm. A 2 mm × 2 mm × 5 mm uncoated Er:GYSGG crystal with parallel and polished end faces was mounted in a copper holder with indium foil to provide a good thermal connection. A water-cooled heat sink allows maintaining the temperature of the crystal at 15 °C. A plane–plane cavity was utilized as a resonator with cavity lengths of 12, 15, and 18 mm. A glass plate with antireflection coating of HT > 95% at 968 nm and reflectivity of 100% at 2.79 μm was used as the input mirror. An output mirror ($CaF_2$ substrate) with different transmissions of 0.5%, 2%, 5%, and 15% at 2.79 μm was employed in the experiments to obtain the optimal laser output. The laser spectrum was also measured by an FLSP 920 fluorescence spectrometer.

Given the strong water absorption in the wavelength region of 2.7–3 μm, the spectral measurement and laser experiment were performed at 25 °C and 20% relative humidity.


**Fig. 1.** Photograph of the as-grown Er:GYSGG laser crystal.

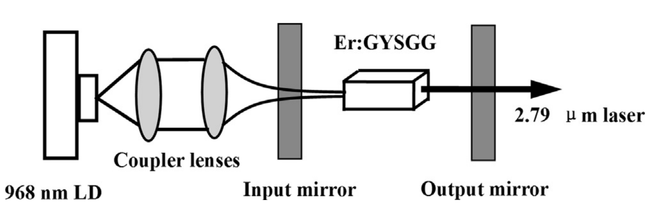


**Fig. 2.** Experimental setup of the Er:GYSGG laser.

## 3. Results and discussion

The absorption spectra of the Er:GYSGG crystal before and after 100 Mrad gamma-ray irradiation are exhibited in Fig. 3. The inset (a) of Fig. 3 shows the corresponding difference spectrum. The color center absorption generated by the irradiation can be easily observed only in the short wavelength region. The inset (b) of Fig. 2 shows that 100 Mrad gamma irradiation has almost no influence on the absorption coefficient of the Er:GYSGG crystal when the wavelength range is above 950 nm, particularly in the pumping wavelength of 965–970 nm and the laser region of 2.7–3 μm. Therefore, these results demonstrate that the Er:GYSGG crystal is a good resistant laser material against gamma radiation.

The fluorescence spectrum of the Er:GYSGG crystal excited by 968 nm LD is shown in Fig. 4. The strongest peak is observed at 2796 nm. The OPO-excited fluorescence decay curves of 2.796 and 1.530 μm show a single exponential decay behavior. In Er:GYSGG, the lifetimes of the upper level $^4I_{11/2}$ and lower level $^4I_{13/2}$ are 1.2 and 3.9 ms, respectively (inset of Fig. 3). In Er:GSGG, the lifetimes of the upper level $^4I_{11/2}$ and lower level $^4I_{13/2}$ are 1.3 and 7.5 ms, respectively. In Er:YSGG, the lifetimes of the upper level $^4I_{11/2}$ and lower level $^4I_{13/2}$ are 1.3 and 3.4 ms, respectively. These results indicate that the partial replacement of $Gd^{3+}$ by $Y^{3+}$ in Er:GSGG can keep the lifetime of the upper level $^4I_{11/2}$ unchanged and significantly decrease the lifetime of the lower $^4I_{13/2}$ level, which is close to that of Er:YSGG. This replacement is advantageous to the 2.7–3 μm laser performance.

Fig. 5 shows the laser output energy as a function of the input pump energy for different transmissions of output coupling mirror. The pump laser was operated at a repetition rate of 50 Hz and a pulse width of 2 ms. As seen the output coupler with a transmission of 2% produces optimal results. A maximum laser energy of 2.43 mJ is obtained, corresponding to a peak power of 1.25 W. Linear fitting results show an optical–optical conversion efficiency of 6.7% and a slope efficiency of 7.2%. The maximum

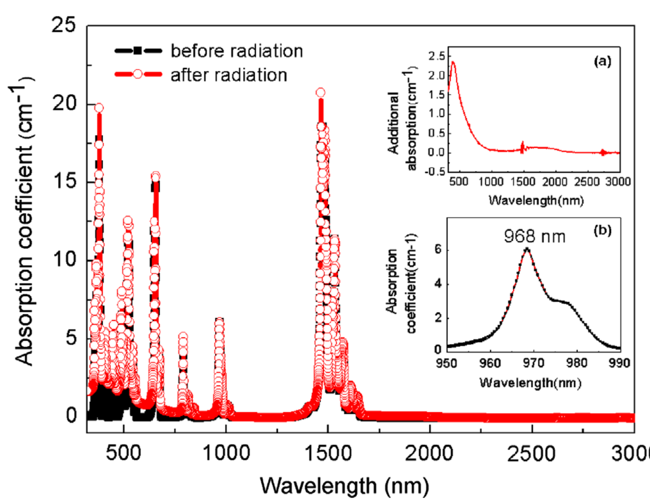


**Fig. 3.** Absorption spectra of Er:GYSGG before and after 100 Mrad gamma-ray irradiation. Inset (a): additional absorption values versus the wavelength and inset (b): enlarged absorption coefficient curve in the range of 900–990 nm.