Spectroscopic and laser properties of Er:LuGG crystal at \(\sim 2.8 \mu m\)

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We report \(\sim 2.8 \mu m\) emission of Er\(^{3+}\)-doped Lu\(_2\)Ga\(_5\)O\(_{12}\) (LuGG) crystal, as well as its laser performance. The continuous-wave (CW) and passively Q-switched lasers were both obtained for the first time at room temperature under 967 nm laser diode end pumping. A 384 mW of CW output power was obtained under the absorbed pump power of 3.28 W, corresponding to an optical-to-optical efficiency of 11.7%; the slope efficiency was 14.1%. A passively Q-switched laser with a maximum average output power of 274 mW was also achieved by utilizing a Bi\(_2\)Te\(_3\)/graphene heterostructure saturable absorber (SA). The shortest Q-switched pulse duration and the repetition rate were 340 ns and 135 kHz, respectively.

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Because the strong absorption peak of water and biological tissues is located at around 3.0 \(\mu m\), solid-state laser sources in this spectral region have been attracting interests for a large number of applications such as medical surgery, dentistry, eye-safe laser radar and sensing technologies.\(^5\,6\) Meanwhile, these lasers can also be utilized as a pumping source to generate far-infrared lasers by using optical parametric oscillation (OPO) technology.\(^6\,7\) Compared to other rare-earth ions such as Ho\(^{3+}\), Er\(^{3+}\)-doped crystals are more suitable for generating 2.7–3.0 \(\mu m\) lasers since they can be pumped efficiently by commercial laser diodes (LDs) at 795 or 975 nm wavelengths. Moreover, the Er\(^{3+}\)-doped crystal possesses a large emission cross-section; thus, it is easy to achieve the high-power and high efficiency laser.

However, the main encountering problem of Er\(^{3+}\)-doped crystals is the intrinsic self-terminating \(^4I_{15/2} \rightarrow ^4I_{13/2}\) transition, which has been a restriction on the laser power and efficiency.\(^5\,6\) It originates from the much longer lifetime of the lower level \(^4I_{13/2}\) compared with that of the upper level \(^4I_{15/2}\). This defect can be overcome by improving the doping concentration of Er\(^{3+}\) ions in laser crystals, such as in Y\(_2\)Al\(_5\)O\(_{12}\) (YAG), Y\(_3\)Sc\(_2\)Ga\(_5\)O\(_{12}\) (YSGG) and Gd\(_2\)Ga\(_5\)O\(_{12}\) (GGG) crystals;\(^13\,15\) notably, the population of the \(^4I_{13/2}\) level will be rapidly depleted through the interaction \(^4I_{13/2} + ^4I_{13/2} \rightarrow ^4I_{11/2} + ^4I_{9/2}\) transition among Er\(^{3+}\) ions.\(^16\,17\)

Nevertheless, high concentration doping of Er\(^{3+}\) ions leads to several additional difficulties. Aside from the increasing difficulty of crystal growth, the thermal conductivity declines with the increment of Er\(^{3+}\) doping concentration, which may severely reduce laser performance. For example, thermal conductivity of the Er:YAG crystal tends to drop by more than 35% with increasing Er\(^{3+}\) doping level.\(^18\) Other Er\(^{3+}\)-doped yttrium compounds have similar trends. Compared with yttrium (Y) compounds, lutetium (Lu) counterparts are more suitable for doping Er\(^{3+}\) ions because of the small differences of both ionic radii and atomic mass between the dopant Er and host Lu ions, which have already been confirmed in the case of Er:Lu\(_2\)O\(_3\).\(^18\) In addition, due to the familiar radius between Er\(^{3+}\) and Lu\(^{3+}\) ions, Er\(^{3+}\)-doped lutetium based garnets possess low distortion of crystal lattice and high uniformity of Er\(^{3+}\) ions concentration.

In the family of gallium garnets, Lu\(_2\)Ga\(_5\)O\(_{12}\) (LuGG) was proved to be an ideal laser host, which possesses the advantages of high thermal conductivity (8.5 W m\(^{-1}\) k\(^{-1}\) at 300 K),\(^19\) high hardness, good chemical stability, and relatively low phonon energy (\(\sim 765 \text{ cm}^{-1}\)).\(^20\) Therefore, it is indicated that the Er:LuGG crystal is a promising gain medium for generating mid-infrared lasers. However, up to now, luminescence properties and laser performances of the Er:LuGG crystal at \(\sim 3.0 \mu m\) have not been reported. In the present work, the absorption and luminescence properties of the Er:LuGG crystal were measured. The continuous-wave (CW) Er:LuGG laser at 2798 nm was achieved. Moreover, a Q-switching laser was also realized by utilizing a Bi\(_2\)Te\(_3\)/graphene heterostructure SA.

In this work, the Er:LuGG single crystal was grown by the Czochralski method. The Lu\(^{3+}\) and Er\(^{3+}\) concentrations in the Er:LuGG crystal were measured by inductively coupled plasma atomic emission spectrometry analysis. For the measurement of absorption and luminescence spectrum, the crystal sample was cut to the size of 3 \(\times\) 3 \(\times\) 1.4 mm\(^3\) with polished end surfaces. A Lambda 950 FT-IR spectrophotometer (Perkin-Elmer, USA) was used to measure the visible and near-infrared absorption spectrum. A 967 nm OPO laser with the pulse width of 5 ns was employed to excite the fluorescence emission, which was recorded by the FSP920 spectrophotometer (Edinburgh Instruments).

The experimental configuration of the Q-switched Er:LuGG laser with a Bi\(_2\)Te\(_3\)/graphene (Bi\(_2\)Te\(_3\)/G) SA is shown in Fig. 1. A fiber-coupled InGaAs LD operating at wavelength of 967 nm was employed as the pump source. The fiber core diameter and the numerical aperture were 200 \(\mu m\) and 0.22, respectively. By using a 1:1 collimation and focus system, the spot diameter of the pump beam focused in the crystal was about 200 \(\mu m\). A 5 mm thick Er:LuGG crystal with a cross section of 2 mm \(\times\) 2 mm was wrapped with indium foil and enclosed by a copper heat sink maintaining the temperature of the crystal at about 15 °C. Both end faces of the crystal were parallel and polished without an anti-reflection...
(AR) coating. A CaF$_2$ flat mirror with an AR coating for 967 nm (T > 90%) and high-reflection (HR) coating for 2.7–2.9 μm (R > 99.8%) was used as the high-reflectivity pump mirror (HRM). An output coupling (OC) with a curvature radius of 500 mm and the transmittance of 2% at 2.7–2.9 μm was used. A simple linear cavity configuration with the cavity length of about 37 mm was employed for achieving efficient passively Q-switched laser. The Bi$_2$Te$_3$/G SA mirror was prepared from the Bi$_2$Te$_3$/G heterostructure by a drop-coated method on a CaF$_2$ mirror of 1 mm in thickness. Morphology and nonlinear absorption characteristics of Bi$_2$Te$_3$/G were discussed in a previous report. Considering the Bi$_2$Te$_3$/G is a kind of broadband saturable absorption, the residual pump radiation would have an impact on the SA mirror. Therefore, the SA mirror was placed near the OC. The Er:LuGG crystal was placed close to the HRM at a range of only 2 mm. The setup for the CW laser operation was similar to Fig. 1, except that it had no SA and the length of the oscillator was shortened up to 12 mm. A thermopile power meter (LPE-1B) was used for measuring the average output power. Meanwhile, the laser wavelength was measured with a Bristol Instruments 821B-IR wavelength meter. The IR-sensitive camera used for recording the beam spatial distribution of the laser was Pyrocam III from Ophir-Spiricon, Inc.

The Er$^{3+}$ ion concentration of the grown Er:LuGG crystal was measured to be 2.6 × 10$^{21}$ ions cm$^{-3}$. Due to the initial Er$^{3+}$ ions concentration of 20.0 at% in raw material, effective Er$^{3+}$ segregation coefficient was evaluated as 1.06. By virtue of the Er$^{3+}$ segregation coefficient in the Er:LuGG crystal which is very close to 1, Er$^{3+}$ ions concentration in the grown crystal has a good uniformity. This also verifies the previously mentioned advantage that LuGG is a suitable host material for Er$^{3+}$ ion doping. The absorption spectrum at room temperature of the Er:LuGG is shown in Fig. 2(a). The crucial absorption peak at 967.5 nm with a full width half
maximum (FWHM) of \( \sim 10 \text{ nm} \) is assigned to the transitions from the ground level \( ^{4}\text{I}_{15/2} \) to the upper level \( ^{4}\text{I}_{11/2} \). The absorption cross-section is \( 4.33 \times 10^{-21} \text{ cm}^2 \) at wavelength around 967.5 nm. It means that the Er:LuGG could be efficiently pumped by the commercial LD at \( \sim 970 \text{ nm} \) wavelength.

Figure 2(b) presents the mid-infrared (MIR) fluorescence spectrum of the Er:LuGG crystal under 967 nm laser excitation. Several emission bands centered at around 2636, 2706, 2798, 2822, 2879 and 2926 nm were observed in 2.6–3.0 \( \mu \text{m} \) wavelength range, which result from the transitions of stark sub-levels from \( ^{4}\text{I}_{11/2} \) to \( ^{4}\text{I}_{13/2} \). The maximum emission cross section of the Er:LuGG crystal is estimated to be \( 4.26 \times 10^{-20} \text{ cm}^2 \). Further, fluorescence decay curves of \( ^{4}\text{I}_{13/2} \) and \( ^{4}\text{I}_{11/2} \) levels of the Er:LuGG crystal were also measured, which are shown in Figs. 2(c) and 2(d). The lifetimes of the \( ^{4}\text{I}_{11/2} \) and \( ^{4}\text{I}_{13/2} \) levels were calculated to be 0.7 and 10 ms, respectively.

The MIR laser was operating in CW mode without the Bi\text{2}Te\text{3}/G SA. The laser output power as a function of absorbed pump power is demonstrated in Fig. 3(a). With an absorbed pump power of 3.28 W, a maximum average output power of 384 mW was achieved. The laser threshold was 578 mW and the slope efficiency was fitted to be 14.1%. The optical-to-optical efficiency was 11.7%. For the absorbed pump power exceeding the threshold, the center wavelength of the laser was located at 2.705 \( \mu \text{m} \) with a FWHM of 0.2 nm. When the absorbed pump power was increased to 1.55 W, the laser wavelength of 2798 nm began to oscillate, with an output power of 142 mW. Then the laser was operating at the dual-wavelength oscillating mode. After the absorbed pump power exceeded 2.84 W, corresponding to the output power of 325 mW, the laser spectrum became single wavelength at 2798 nm. This wavelength-switching may be explained by the transition selection under the condition of different distribution of the population in the upper and lower laser level. A similar trend has been observed in Er:GGG and Er:YAG crystals.2,23)

In passively Q-switched lasers with Bi\text{2}Te\text{3}/G SA, the heat effect of SA caused by the residual pump laser will increase nonsaturable losses and then provoke Q-switching instabilities. A convenient method adopted to alleviate this detrimental...
The average output power and the pulse energy calculated as a function of the pump power are shown in Fig. 4(a). It is observed that the average output power and the pulse energy increase almost linearly with the absorbed pump power. The maximum average output power was 274 mW with the pulse energy of 2.03 μJ. According to the pulse width and the repetition rate recorded, the maximum pulse peak power can be calculated to be about 6 W. Compared with the CW laser performance, the intra-cavity optical losses caused by the SA mirror makes a remarkable decline in average output powers. The variation of the pulse repetition rate and the pulse duration with the absorbed pump power is presented in Fig. 4(b). Within the absorbed pump power range of 1.02 W to 3.28 W, the repetition rate increased from 30.5 kHz to 135 kHz, while the pulse duration decreased from 1.53 μs to 340 ns. The pulse width of 340 ns is very close to the shortest duration reported of 335 ns for nano-SAs Q-switched ~3 μm Er lasers. Stable pulse trains at the absorbed pump power of 3.28 W and a pulse envelop at the pulse width of 340 ns are shown in Fig. 5.

The wavelength of the Q-switched laser was determined by the absorbed pumped power, which was in accordance with the variation in CW laser. The output beam quality factor at the maximum average output power of 274 mW was measured by the traveling knife-edge method, as shown in Fig. 6(a). The data were fitted by a standard Gaussian beam propagation expression. The beam quality factors along the x-axis and y-axis were calculated to be $M_x^2 = 1.42$ and $M_y^2 = 1.43$, respectively. The value of $M^2$ remained almost constant through the full pump power range in both directions. We attribute it to the weak thermal lens effect in the Er: LuGG crystal. The two-dimensional and three-dimensional transverse beam profiles of the Q-switched Er:LuGG laser monitored by the IR-sensitive camera are shown in Figs. 6(b) and 6(c), respectively. The images revealed that the laser beam was nearly circular and the laser oscillated with a Gaussian distribution of the electrical field. A possible way to further enhance the output power is adjusting the Er$^{3+}$ concentration and the transmittance of the output coupling.

Though the lifetime of lower laser level $^4I_{13/2}$ is much higher than the upper laser level $^4I_{11/2}$, the CW and passively Q-switched laser were both realized. We attribute this to the difference in populations of the lower laser level $^4I_{13/2}$ under different pumping conditions. Different from fluorescence decay curves measurement excited by a low excitation with a short pulse at about a several nanoseconds level, for laser operation, pumped by a CW 987 nm LD will result in a large population density of the lower laser level $^3I_{13/2}$. In this case, the odds of the energy transfer process $^4I_{13/2} + ^4I_{13/2} \rightarrow ^4I_{11/2} + ^4I_{9/2}$ increase significantly. This energy transfer process would further decrease the population of the lower laser level $^4I_{13/2}$. Therefore, the lower laser level ($^4I_{13/2}$) lifetime of laser operation was shorter than the value fitted by fluorescence decay curves. For this reason, many Er$^{3+}$ doped crystals could realize CW lasers in spite of having a long lifetime of lower laser level $^4I_{13/2}$.

In conclusion, CW and passively Q-switched Er:LuGG laser at 2798 nm were demonstrated for the first time to the best of our knowledge. Under an absorbed pump power of 3.28 W, the CW laser with the maximum output power of 384 mW was achieved. Moreover, stable passive Q-switching operation with the maximum average output power of 274 mW was generated by utilizing the Bi$_2$Te$_3$/G SA. Pulses as short as 340 ns under a repetition rate of about 135 kHz were realized with a pulse energy of 2.03 μJ and a peak power of 6 W. The experimental results definitely demonstrate that Er:LuGG could be a very promising laser gain medium for solid-state CW and pulsed 3 μm lasers.

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