A quasi four-level solid-state laser is provided. A laser crystal is disposed in a laser cavity. The laser crystal has a LuAG-based host material doped to a final concentration between about 2% and about 7% thulium (Tm) ions. For the more heavily doped final concentrations, the LuAG-based host material is a LuAG seed crystal doped with a small concentration of Tm ions. Laser diode arrays are disposed transversely to the laser crystal for energizing the Tm ions.

8 Claims, 1 Drawing Sheet
1

QUASI FOUR-LEVEL TM:LUAG LASER

STATEMENT OF GOVERNMENT INTEREST

This invention was made with Government support under contract NAS1-19603 awarded by NASA. The Government has certain rights in this invention.

CROSS-REFERENCE TO RELATED PATENT APPLICATIONS

This patent application is related to co-pending patent application entitled "FLASHLAMP-PUMPED Ho:Tm:Cr:LuAG LASER", Ser. No. 08/593,791, filed on Jan. 29, 1996.

FIELD OF THE INVENTION

The invention relates generally to lasers, and more particularly to quasi four-level lasers operating at room temperature in the 2 μm wavelength region.

BACKGROUND OF THE INVENTION

Quasi four-level solid-state lasers operating in the 2 μm wavelength region are used for sensing wind velocity, as optical pumps for mid-infrared parametric oscillators, for remote sensing of water vapor or carbon dioxide, for medical applications such as laser angioplasty, for material processing applications, and for communications.

In general, quasi four-level lasers operating in the 2 μm wavelength region utilize laser material made from a host material doped with laser active ions from the group of rare earth ions such as holmium (Ho) and thulium (Tm), transition metal ions such as chromium (Cr) or combinations thereof. The host materials for such lasers come from the group of crystals such as YAG, YLF, YSGG, GSGG, GSAG, YSAG, YAIO, GGG, YGG and LLGG. To date, the Tm:YAG and Tm:YLF lasers have provided the best performance for diode-pumped, quasi four-level lasers operating at room temperature. However, the thresholds of these lasers are relatively high which can lead to thermal stresses in the laser crystals or rods as higher input energies are required.

SUMMARY OF THE INVENTION

Accordingly, it is an object of the present invention to provide a quasi four-level laser that operates at room temperature and has a reduced threshold for laser action.

Other objects and advantages of the present invention will become more obvious hereinafter in the specification and drawings.

In accordance with the present invention, a quasi four-level solid-state laser is provided. A laser cavity is defined by reflective elements or mirrors having a host material that is doped with thulium (Tm) ions. More specifically, the host material is either a pure LuAG seed crystal or a LuAG seed crystal doped with concentrations of between about 2% and 4.5% Tm ions. The percent concentration is defined herein as the percentage of Tm doping ions that are measured as being present in the doped material.

The rods used for laser rod 12 were fabricated from crystals grown with the Czochralski method. The raw materials used were four nines pure Lu₂O₃ with major impurity being Tm at 300 parts in 10⁶ (ppm), and five nines plus pure Al₂O₃. The materials were mixed with 0.005 excess Lu₂O₃ to a formulation of Lu₃(0.955-0.045)Tm₄Al₂O₁₂. The mixing crucible had a 0.45 liter capacity and was made of pure iridium metal. Melting was accomplished in a radio-frequency heated zirconia furnace.

The seed crystal was fabricated from a (111) oriented LuAG rod. For the smaller final concentrations of Tm doping, Tm ions were mixed with a host material that consisted of a pure LuAG seed crystal. However, for the more heavily doped final concentrations of Tm, the host material was a doped LuAG seed crystal. More specifically, Sample I is based on a host material of a pure LuAG seed crystal that is doped to a final concentration of 2% Tm ions. Sample II is based on a host material of a 2% Tm-doped LuAG seed crystal that is then doped to a final concentration of 4% Tm ions. Sample III is based on a host material of a 4% Tm-doped LuAG seed crystal that is then doped to a final concentration of 7% Tm ions.

A Tm-doped LuAG seed crystal for the more heavily doped final concentrations of Tm is used because there is some lattice mismatch when the more heavily doped Tm:LuAG crystal is grown using pure LuAG as the seed crystal. By starting with a seed crystal that is doped to a lesser or equal concentration of Tm ions as compared to the final Tm ion concentration, a laser crystal of improved optical quality is achieved since stresses and strains present during crystal growth are reduced.

For all samples, a growth rate of 2.5 mm/hr was used. The growth was manually controlled to maintain a crystal diam-
An absorption spectrum was taken on a Tm:LuAG sample in the spectral region around 0.8 μm. Using these results, the absorption efficiency was calculated as a function of the center wavelength of the diode array. Based on these results, for a diode array spectral bandwidth of 0.003 μm, the optimum wavelength for the laser diode arrays is 0.782 μm. Thus, Tm:LuAG is compatible with GaAlAs diode pumping.

Three GaAlAs laser diode arrays, i.e., laser diode arrays 18, were arranged symmetrically about the periphery of the various Tm:LuAG samples used for laser rod 12. The three laser diode arrays were used to transversely pump the Tm:LuAG laser. The center wavelength of the laser diode arrays was 0.782 μm. The optical output of the diode arrays was measured in a separate experiment with a calibrated integrating sphere to collect all the diode array output energy. When pulse lengths of 1.0 ms were used, the maximum optical energy available from the laser diode arrays was 1.126 J.

Laser 10 was operated at room temperature, e.g., between about 15 °C to 21 °C, for each of Samples I, II and III. Such operation is characterized as maintaining laser rod 12 in a room temperature environment during operation of laser 10. Performance data was recorded using the above-described arrangement of laser diode arrays.

Each of Samples I, II and III was 4.0 mm in diameter and 10.0 mm in length to correspond with the length of the diode arrays. End surfaces of each sample rod were flat and normal to the axis of the sample rod and antireflection coated at 2.1 μm. Lateral surfaces of each sample rod were finished with a fine grind.

A gold coating on each reflector face 19A provided for a high reflectivity around 0.8 μm. Because the refractive index of LuAG is high (approximately 1.9), the divergence of the diode arrays is reduced considerably thereby permitting most of the pump radiation to be reflected back into laser rod 12 by each reflector face 19A. Use of three symmetrically placed laser diode arrays provided an efficient, transverse-pumping coupling geometry. As shown in FIG. 2, the diode arrays 18 120° apart provided a geometry in which each diode array faced a corresponding reflector/heat sink 19 in contact with and on the opposite side of laser rod 12. Each of reflectors/heat sinks 19 had a face 19A with a width of approximately 1.5 mm. Each face 19A was diametrically opposed to one of laser diode arrays 18. Cooling to 15 °C to 21 °C was possible with the low gain of the Tm transition as fast as the concentration. This supports the observation that the absorption efficiency is still increasing but not as fast as the Tm concentration.

Table 1 for each of Samples I, II and III.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Mirror Reflectivity</th>
<th>Threshold (μJ)</th>
<th>Slope Efficiency</th>
<th>Wave Length (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.98</td>
<td>0.556</td>
<td>0.1186</td>
<td>2.0225</td>
</tr>
<tr>
<td>II</td>
<td>0.98</td>
<td>0.494</td>
<td>0.1693</td>
<td>2.0238</td>
</tr>
<tr>
<td>III</td>
<td>0.98</td>
<td>0.731</td>
<td>0.2036</td>
<td>2.0336</td>
</tr>
</tbody>
</table>

Laser operation with output mirrors of lower reflectivities was not possible because of the low gain of the Tm transition and the limited amount of pump energy. Only Sample II produced useful output with any mirror except the highest available reflectivity of 0.98. For example, laser operation of Sample II was obtained with a 0.95 reflecting output mirror. However, threshold increased by a factor of approximately 1.5 to 0.777 J.

The threshold does not increase as fast as the Tm concentration increases thereby indicating that the increased absorption efficiency (and possibly the increased quantum efficiency) tends to offset the increased population density in the lower laser level. Calculated absorption efficiencies as the final Tm concentration increases from 2% to 4% support this contention. As the final Tm concentration increases from 4% to 7%, the threshold increases more rapidly, although not as fast as the concentration. This supports the observation that the absorption efficiency is still increasing but not as fast as the Tm concentration.

Slope efficiency increases with increasing final Tm concentration almost exactly at the same rate as absorption efficiency increases with Tm concentration thereby indicating a nearly constant quantum efficiency. Although optical transparency is required for threshold to be achieved, slope efficiency depends only on incremental changes in the energy delivered to the upper laser manifold with increasing
optical pump energy. As such, slope efficiency depends directly on the product of the absorption and quantum efficiencies, both of which can increase with increasing Tm concentration. The ratio of the absorption efficiencies for Sample I to Sample II to Sample III is 1.00:1.45:1.72, and the ratio of the differential absorption efficiencies is 1.00:1.43:1.71. Since the ratios are nearly the same, the quantum efficiencies can be considered to be the same.

The wavelength of the laser depends on the final concentration of Tm in the laser rod. The wavelength of the Tm:LuAG was measured with a 0.5-m Ebert monochromator with a 600 g/mm grating. The output of the monochromator was detected with an InSb detector and recorded as a function of wavelength. The peak emission wavelength was found to be approximately 2.023 μm for Samples I and II and approximately 2.034 μm for Sample III.

Operation of the laser rod with the higher Tm concentration at a longer wavelength is not unexpected. With a higher concentration, achieving optical transparency is more difficult because the population density of the lower laser level is directly proportional to the Tm concentration. Presumably, the longer wavelength is associated with a higher level in the lower laser manifold, which would have a lower thermal occupation factor and probably a lower effective stimulated emission cross section.

The advantages of the present invention are numerous. The quasi four-level Tm:LuAG laser operates at room temperature and achieves a low threshold for energy when compared to other quasi four-level lasers operating in the 2 μm wavelength region.

2. A quasi four-level solid-state laser crystal as in claim 1 wherein said narrowband energizing source is at least one laser diode array.

3. A quasi four-level solid-state laser crystal as in claim 2 wherein said at least one laser diode array is a GaAlAs laser diode array.

4. A quasi four-level solid-state laser crystal as in claim 1 wherein said LuAG-based host material is a LuAG seed crystal doped with a concentration of about 2% Tm ions, and wherein said final concentration of Tm ions is about 4% Tm ions.

5. A quasi four-level solid-state laser rod having improved optical quality for use in a laser cavity maintained at room temperature and defined by a reflective element that is completely reflective and a second reflective element having a reflectivity of 0.98, said first reflective element and said second reflective element being arranged on a common axis to form a reflective path therebetween, said laser rod disposed in said laser cavity along said common axis, said laser rod comprising a LuAG-based host material doped to a final concentration of Tm ions between about 4% and about 7% Tm ions, wherein said LuAG-based host material is a LuAG seed crystal doped with a concentration of between about 2% to 4% Tm ions and wherein said final concentration of Tm ions is less than said final concentration of Tm ions, wherein said improved optical quality results as lattice mismatch present during growth of said laser rod is reduced, and wherein when a plurality of laser diode arrays is disposed transversely to and symmetrically about said laser rod for energizing said Tm ions, said laser rod requires a lower threshold energy when compared to other quasi four-level lasers operating in the 2 μm wavelength region.

6. A quasi four-level solid-state laser crystal as in claim 5 wherein each of said plurality of laser diode arrays is a GaAlAs laser diode array.

7. A quasi four-level solid-state laser crystal as in claim 5 wherein said plurality of laser diode arrays comprises an odd number of laser diode arrays.

8. A quasi four-level solid-state laser crystal as in claim 5 wherein said LuAG-based host material is a LuAG seed crystal doped with a concentration of about 2% Tm ions, and wherein said final concentration of Tm ions is about 4% Tm ions.