DEVELOPMENT OF FLASHLAMP-PUMPED Q-SWITCHED
Ho:Tm:Cr:YAG LASERS FOR MID-INFRARED LIDAR APPLICATION

557 - 36

266 38

R

Young S. Choi, Kyong H. Kim, and Donald A. Whitney
Department of Physics
Hampton University
Hampton, Virginia

Robert V. Hess, Norman P. Barnes, Clayton H. Bair, and Philip Brockman
NASA Langley Research Center
Hampton, Virginia

ABSTRACT

A flashlamp-pumped 2.1 μm Ho:Tm:Cr:YAG laser has been studied for both normal mode and Q-switched operations under a wide variety of experimental conditions in order to optimize performance. Laser output energy, slope efficiency, threshold and pulselength were determined as a function of operating temperature, output mirror reflectivity, input electrical energy and Q-switch opening time. The measured normal-mode laser thresholds of a Ho^{3+} (0.45 atomic %) :Tm^{3+} (2.5 at. %) :Cr^{3+} (0.8 at. %) : YAG crystal ranged from 26 to 50 J between 120° and 200° Kelvin with slope efficiencies up to 0.36% with a 60% reflective output mirror. Under Q-switched operation the slope efficiency was 90% of the normal-mode result.

DEVELOPMENT OF FLASHLAMP-PUMPED Q-SWITCHED
Ho:Tm:Cr:YAG LASERS FOR MID-INFRARED LIDAR APPLICATION

Introduction

Development of solid state lasers with Ho^{3+}, Tm^{3+} and(or) Er^{3+} doped crystals has been pursued by NASA for eye-safe mid-infrared LIDAR (light detection and ranging) application. As a part of the project we have been working on evaluation of Ho^{3+}:Tm^{3+}:Cr^{3+}:YAG crystals for normal-mode and Q-switched 2.1 μm laser operations in order to determine an optimum Tm^{3+} concentration under flashlamp pumping conditions.

Lasing properties of the Ho^{3+} in the mid-infrared region have been studied by many research groups since the early 1960's.[1-5] However, the technology of those lasers is still premature for lidar application. In order to overcome the inefficiency related to narrow absorption bands of the Ho^{3+}, Tm^{3+} and Er^{3+}, the erbium has been replaced by chromium. The improvement in flashlamp-pumped Ho^{3+} laser efficiency has been demonstrated recently by several research groups[6,7] by utilizing the broad absorption spectrum of Cr^{3+} which covers the flashlamp's emission spectrum. Efficient energy transfer to the Tm^{3+} and then the Ho^{3+} occurs subsequently. It is known that high Tm^{3+} concentration and low Ho^{3+} concentration are preferred to achieve a quantum efficiency approaching two and to avoid large reabsorption losses.[6] However, determination of the optimum Tm^{3+} concentration required to ensure efficient energy transfer from Cr^{3+} to Tm^{3+} and from Tm^{3+} to Ho^{3+} has not been made in the Ho:Tm:Cr:YAG crystal. This paper will present the results obtained so far with one out of the three Ho:Tm:Cr:YAG crystals with three different Tm^{3+} concentrations with similar Cr^{3+} and Ho^{3+} concentrations.

Quantum Processes in Ho^{3+}, Tm^{3+} and Cr^{3+} -Ions

The energy levels of the Cr^{3+}, Tm^{3+} and Ho^{3+}-ions and the energy transfer mechanisms among the ions in a YAG crystal are illustrated in Fig. 1. The use of Cr^{3+} for flashlamp pumping is based on its broad absorption spectrum provided by the transitions from the ground $^4A_2$ state to the upper $^4T_1$ and $^4T_2$ states. Subsequently, efficient near resonant energy transfer to the $^3H_4$ state of the Tm^{3+} occurs. Fig. 2 shows the absorption spectrum of the Ho^{3+} (0.45 atomic %) :Tm^{3+} (2.5 at. %) :Cr^{3+} (nominally 1.5 at. %) :YAG crystal. The chromium concentration of 1.5 atomic % stated by vendor turns out to be 0.8 atomic % based on absorption measurement. The two broad bands in the visible region correspond to the chromium absorption while the other sharp peaks correspond to the absorption by the holmium and thulium ions. Armagan, et al.'s work (Ref. 8) showed that the energy transfer processes are more effective in crystals with low Cr^{3+} and high Tm^{3+} concentrations.

For high Tm concentrations, the transition from the $^3H_4$ manifold to the $^3F_4$ manifold induces the cross relaxation process which provides two Tm ions in the $^3F_4$ manifold from a single Tm ion in the $^3H_4$ manifold. As a result, the quantum efficiency approaches two. Then, the near resonant energy transfer process from the $^3F_4$ manifold of Tm to the $^5I_7$ manifold of Ho provides an efficient pumping mechanism of the Ho-ions. In order to operate the 2.1 μm Ho laser efficiently at room temperature, the Ho^{3+} concentration must be low. The increase of the Ho^{3+} concentration increases the ground state population of $^5I_8$ of Ho manifold which causes high resonant reabsorption losses for the $^5I_7(Ho)$ -$^5I_8(Ho)$

laser transition. However, as the temperature goes down, the upper levels of the lower laser manifold of the Ho^{3+} become thermally unpopulated. By decreasing the temperature and the population density of the lower laser levels, the efficiency of the laser performance increases. Since the upper laser level lifetime of the Ho^{3+} is longer than 5 ms when at room temperature, efficient storage time for the Q-switched operation is possible. A high holmium ion concentration may be effective for high Q-switched laser output since the population in the $^5I_7$ manifold can be increased.
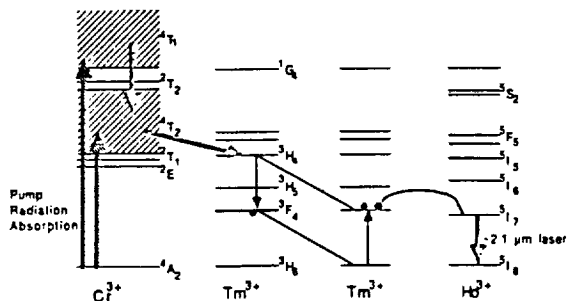

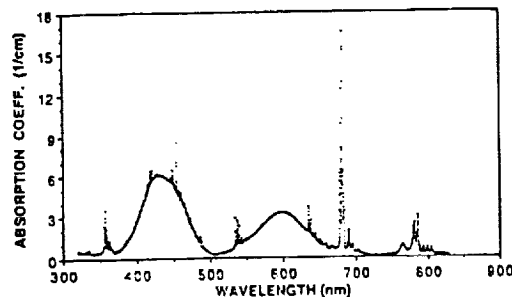Figure 1. Energy transfer processes in a Ho:Tm:Cr:YAG crystal.

Figure 2. Absorption spectrum of the Ho:Tm:Cr:YAG crystal (0.45% Ho, 2.5% Tm, 0.8% Cr).

Experimental Methods

The experimental configuration used in this research is shown in Fig. 3. The temperature of the laser rod was varied from 120°K to room temperature by circulating cold nitrogen gas around the rod. The flashlamp was cooled by circulating deionized water. The flashlamp and laser rod were placed in a pumping cavity made of highly reflective aluminum. This cavity was 76.2 mm long and had an elliptical cross section with major and minor axes of 152.4 mm and 149.1 mm, respectively. The detailed cavity design was reported elsewhere.[9] In order to achieve thermal isolation, the entire pumping cavity was placed in a vacuum system. Good thermal isolation was necessary since the cooling capacity of liquid nitrogen vapor was limited. A 450 torr Xe flashlamp with 4 mm bore diameter and 76.2 mm arc length was used and surrounded by a uranium doped flow tube water jacket to reduce possible solarization effects. The size of the Ho: Tm: Cr: YAG laser rod used was 4 mm in diameter and 55 mm in length.

Since the Ho: TM: Cr: YAG has a long upper laser level lifetime, the pulse forming network (PFN) for the flashlamp was designed for long pulse operations. With a 146.5 μf capacitor and a 184 μH inductor critically damped pulses of 300 μs FWHM pulse length were obtained. At the input voltage of 905 volts required for a critically damped pulse, the electrical input energy was 60 J. A highly reflective mirror at 2.1 μm with a 10 m radius of curvature was attached to one end of the vacuum box as a window, and an antireflection coated quartz flat was place on the other side of the vacuum box. Flat mirrors with various reflectivities were used as output couplers. The total resonator length was 88 cm. In Q-switched operations a lithium niobate crystal ($LiNbO_3$) with dimensions of 9 mm x 9 mm x 25 mm and a ZnSe polarizer of 2.17 mm thickness were used as a Q-switch. The hold-off voltage for the Q-switch crystal was 1.62 kV. The Q-switch trigger signal could be delayed from 0 to several ms with respect to the trigger for the flashlamp.

424

The laser output energy and pulse shape were measured with a pyroelectric energy meter and with a liquid N_2 cooled HgCdTe detector, respectively. The bandwidth of the HgCdTe detector was 10 MHz.
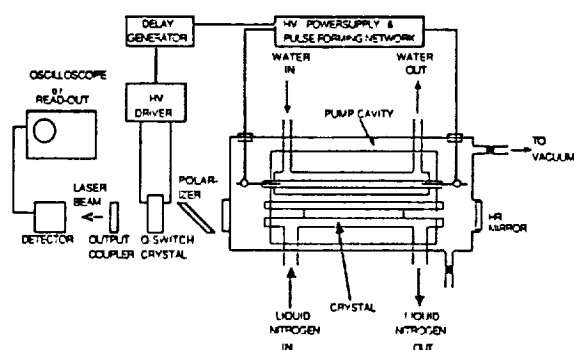

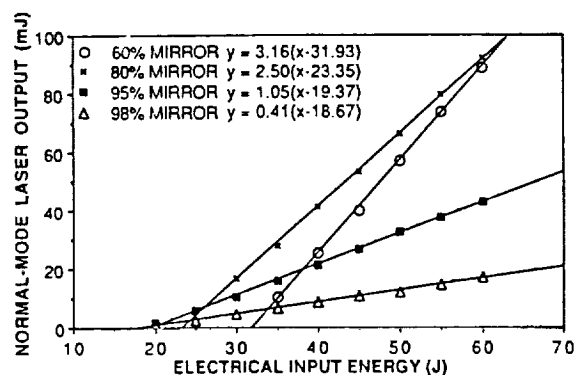Figure 3. Schematic diagram for the experimental setup.

Figure 4. Normal-mode laser output energy of the Ho:Tm:Cr:YAG crystal as a function of electrical input energy at 150 K.

Results

Fig. 4 shows the normal-mode laser output energies of the Ho(0.45%) :Tm(2.5%) :Cr(0.8%) :YAG crystal measured as a function of the electrical energy stored in the capacitor for various output mirror reflectivities at the operating temperature of 150°K. As expected, the slope efficiency and threshold energy increase with the decreasing mirror reflectivity. The measured normal-mode laser output energies as a function of operating temperature at various electrical input energies with a 60% reflectivity mirror are shown in Fig. 5. The decrease of the laser output energy with the increasing temperature clearly indicates the effect due to thermal population in the lower laser level. Figs. 6 and 7 show the dependence of the laser threshold and slope efficiency, respectively, on the operating temperature at various mirror reflectivities. The highest slope efficiency, 0.36 %, was obtained with a 60% mirror at 120 K, while the lowest extrapolated threshold electrical input energy of 14.8 J was achieved at 120 K with a 90% mirror. The low slope efficiency may be attributed to several causes. The laser crystal diameter is relatively small compared to the mode diameter of about 2.8 mm. The Cr^{3+} and Tm^{3+} concentrations in the crystal are low. The laser rod is short compared to the flashlamp and produces poor optical coupling between the flashlamp and the laser rod. Low cavity reflectivity which was less than 80% at 633 nm also causes poor optical coupling.

The measured Q-switched and normal-mode laser outputs are plotted in Fig. 8 as a function of the electrical input energy stored in the capacitor at various temperatures. The output mirror used in this comparative measurement had a 60% reflectivity and the normal-mode operation was done with the Q-switch crystal and ZnSE polarizer in the resonator. The Q-switched laser output and slope efficiency are only slightly lower and the threshold is slightly higher than those of normal mode operation. The observed slope efficiencies are 0.123% for normal-mode and 0.111% for Q-switched operation at the operating temperature of 130°K. The Q-switched slope efficiency of the Ho:Tm:Cr: YAG crystal corresponds to approximately 90% of the normal-mode slope efficiency. The measured wavelength of the Ho:Tm:Cr:YAG laser with a spectrometer was about 2.095 μm.
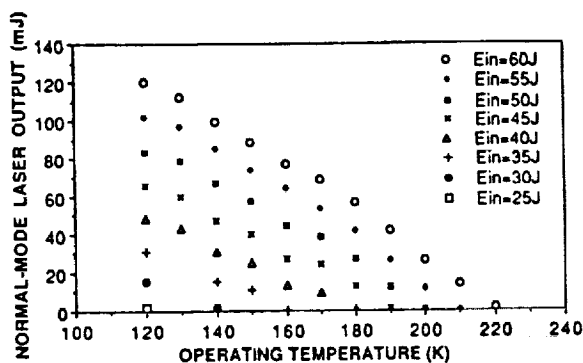
Figure 5. Normal-mode laser output energy as a function of the operating temperature with a 60% reflectivity output mirror.
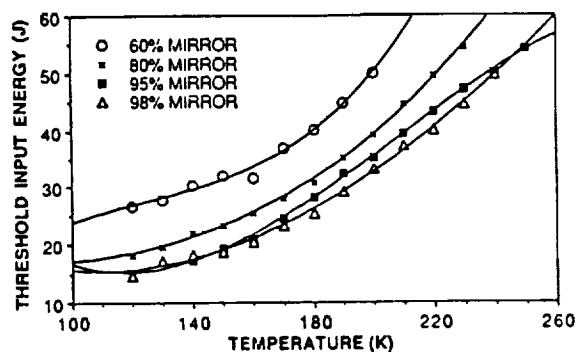

Figure 6. Threshold input electrical energy as a function of the operating temperature with various output mirror reflectivities.
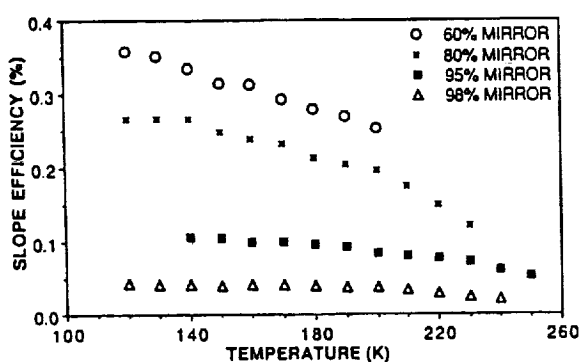

Figure 7. Slope efficiency as a function of temperature with various mirror reflectivities.
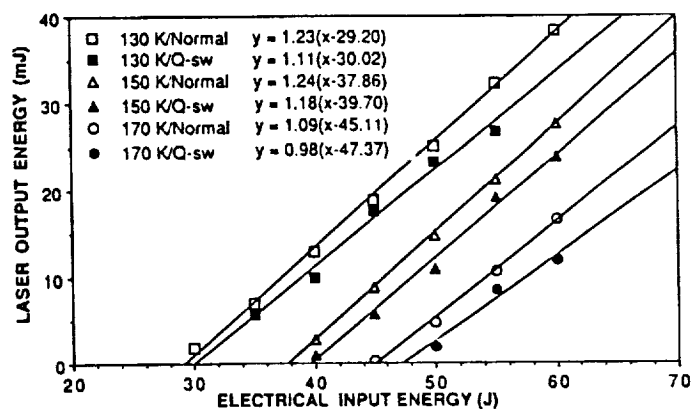

Figure 8. Normal-mode and Q-switched laser output energies as a function of the input energy with a 60% reflective mirror.

Conclusion

A Ho:Tm:Cr:YAG laser with concentrations of 0.45 at. % Ho, 2.5 at. % Tm and 0.8 at. % Cr has been studied for both normal mode and Q-switched 2.1 μm laser operation under flashlamp pumping at various operating temperatures, various output mirror reflectivities, and various input energies. Continuing work on the evaluation of the other two crystals with different Tm^{3+}-ion concentrations is in progress and will provide an optimum Tm concentration in the Ho:Tm:Cr:YAG crystal.

Acknowledgments

References

1. Johnson, L.F., Boyd, G.D., Nassau, K., Proc. IRE, **1962**, 50, 87.

2. Chicklis, E.P., Naiman, C.S., Folweileer, R.C., Gabbe, D.R., Jenssen, H.P., Linz, A. Appl. Phys. Lett. **1971**, 19(4), 119.

3. Barnes, N.P., Gettemy, D.J., IEEE J. Quantum Electron., **1981**, QE-17(7), 1303.

4. Lotem, H., Kalisky, Y., Kagan, J., Sagie, D., IEEE J. Quantum Electron., **1988**, 24(6), 119.

5. Duczunski, E.W., Huber, G., Appl. Phys. Lett., **1986**, 48(23), 1562.

6. Mitzscherlich, P., Tunable Solid-State Lasers II (Edited by Budfor et al.), Springer-Verlag, New York, **1986**, p. 282.

7. Scherbakov, I.A., Tunable Solid-State Lasers II (Edited by Budgor et al.), Springer-Verlag, New York, **1986**, p. 293.

8. Armagan, G., Di Bartolo, ., Buoncristiani, A.M., "Spectroscopic Investigation of the Cr to Tm Energy Transfer in Yttrium Aluminum Garnet Crystals," to be published. (**1989**).

9. Gettemy, D.J., Barnes, N.P., Griggs, E., Rev. Sci. Instrum. **1980**, 51(9), 1194.