技術報告

Performance Characteristics of Acousto-Optic Q-switched Tunable 2.1 μm Ho: YSGG Laser

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This technical note documents the performance characteristics of a flashlamp pumped, acousto-optic (A/O) Q-switched, 2.1 μm Cr : Tm : Ho : YSGG laser. A fused quartz A/O Q-switch was inserted in the Ho laser cavity between the laser rod and the rear mirror, and was modulated by a RF signal of 27.1 MHz. The Q-switched laser pulse energy and pulse width were measured as a function of the delay time of the A/O Q-switch signal, flashlamp input energy, and Ho laser rod temperature. At optimal operating conditions, the Ho : YSGG laser pulse had a pulse energy of 25 mJ and a pulse width of 88 ns; this was obtained with a flashlamp input energy of 156 J, temperature of 16°C, and repetition rate of 3 Hz. Continuous tuning of the Ho laser was obtained over a range from 2.081 μm to 2.087 μm using two uncoated glass intracavity etalons. The linewidth of the laser was approximately 0.1 nm.

1. Introduction

IR tunable solid-state lasers doped with rare earth and transition metals like Er, Ho, Tm, Cr, and Ti are currently being developed, because these lasers have the potential for diode laser pumping, wide tunability, and high average power.[1] We are interested in the development of the 2.1 μm Ho laser as a light source for laser remote sensing of the atmosphere. The Ho laser operates in the so called "eye-safe" spectral region ($\lambda > 1.4$ μm) and is also tunable over a 0.01 μm range near 2.1 μm. This wavelength coincides with several water vapor absorption lines in the atmosphere. Because of these potential attributes, the Ho laser is being actively developed for DIAL (differential-absorption lidar) measurements of water vapor in the atmosphere[2,3] and for coherent Doppler lidar measurements of atmospheric winds for LAWS (NASA/LIDAR Atmospheric Wind Sounder).[4]

For long-range, range-resolved lidar and DIAL applications, a laser pulse of high peak power and short duration is required, which can be obtained only through Q-switched operation of the laser. In the case of the Ho laser, Q-switching techniques have included a mechanical spinning mirror and also a $LiNbO_3$ pockels cell.[3-5] These techniques have some limitations in the operation of the Ho laser. The spinning mirror Q-switch has mechanical vibrations and the repetition rate of the laser is limited by the rotation frequency of a motor. The $LiNbO_3$ Q-switch has problems due to optical damage at high fluence levels if the Q-switch has any residual absorption in the IR wavelength region. Another technique for Q-switching a pulsed laser is to use an acousto-optic (A/O) Q-switch; this technique only works if the gain of the laser cavity is small to moderate, since A/O Q-switches do not normally have exceptional "hold-off" capability. In spite of this limitation, an A/O Q-switch has been used successfully in a lower-power diode laser pumped Ho : YAG laser[6] and has also just recently been used in a higher power flashlamp pumped Ho laser.

In this short technical note, we describe our experimental testing of a commercial Ho laser which used an A/O Q-switch and document for the first time its performance parameters. Our results indicate that the optimal Ho laser performance was obtained at a Ho laser rod temperature of 16°C, a Q-switch delay time of 630 μs, and at an input flashlamp pump energy of approximately 160 J/pulse. Output energy of the Ho laser pulse was approximately 25 mJ and the laser pulse width was 88 ns.

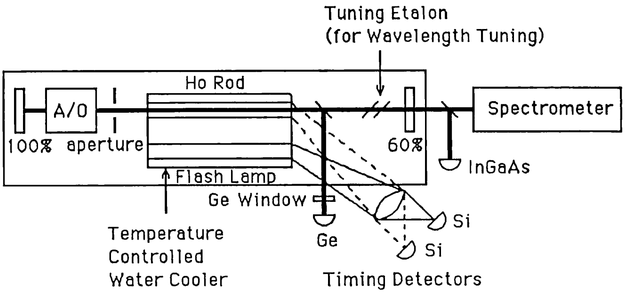

Fig. 1 Schematic diagram of the Ho laser.

2. Experimental Setup

The laser used in this experiment was a commercially available, flashlamp pumped, Ho : YSGG laser (Schwartz Electro-Optics, Laser 1-2-3) ; a schematic diagram of the laser is shown in **Fig. 1.** The laser cavity used a 5 mm×75 mm Ho : YSGG rod with Cr and Tm co-doping to aid in flashlamp operation ; the concentration was 5×10^{19} cm^{-3} Ho, 2×10^{20} cm^{-3} Cr, and 8×10^{20} cm^{-3} Tm. The laser cavity had a 100% reflection rear mirror, 60% reflection output mirror, and a cavity length of 67 cm. A fused quartz A/O Q-switch (Newport Electro-Optics Systems, Model No. N 32027-50-5-2.1) was used in the laser cavity and was modulated with a radio frequency (RF) signal of 27.1 MHz supplied by an RF driver (Newport Electro-Optics Systems, Model No. N 31027-50 DM). The A/O device was placed between the rear mirror and the laser rod. An aperture was inserted between the A/O device and the rod to achieve TEM_{00} single spatial mode laser operation. The pulse energy was measured with an energy meter and the shape of the Q-switch pulse was monitored using a fast rise-time InGaAs (Epitaxx, Model No. ETX 1000 GR 21) photodetector with a high speed amplifier (Analog Module, Model No. 313-1-S). The wavelength of the laser was monitored by a 0.5 m grating spectrometer.

The relative timing of the flashlamp, the build-up of the population inversion of the Ho atoms, and the Q-switch trigger pulse are important in determining the output characteristics of the Ho laser. In order to measure some of these temporal parameters, a Ge detector (with a Ge window) was used in the cavity in order to measure the 1.8 μm fluorescence from the Ho laser rod, a Si detector was used adjacent to the flashlamp to measure the visible output of the flashlamp, and another Si detector was used to measure the green fluorescence from the laser rod. An InGaAs detector monitored the laser output pulse.

3. Results

Figure 2(a) shows a composite photograph of the relative timing of the detected optical and elec-

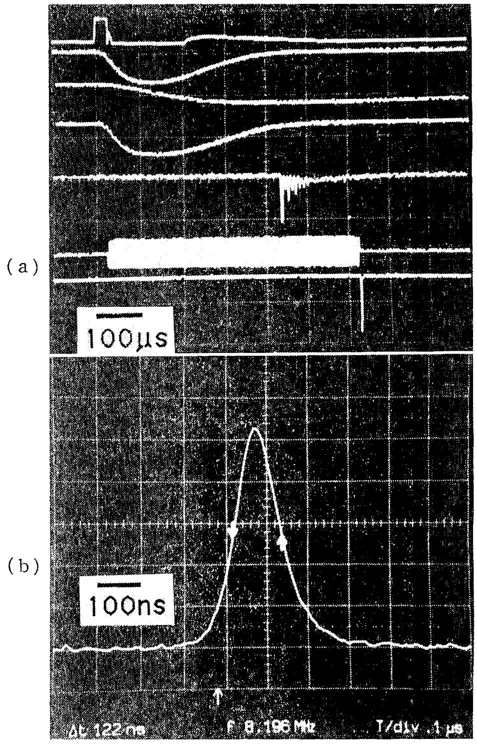

Fig. 2 (a) Photograph of the relative timing of the flashlamp trigger, flashlamp visible output, Ho fluorescence near 1.8 μm, Ho fluorescence in the green wavelength range, normal mode oscillation of the Ho laser (without A/O Q-switch), RF drive signal to the A/O Q-switch, and the Q-switched laser pulse. (b) Photograph of the pulse shape of the Q-switched Ho laser. Laser conditions are flashlamp input energy of 121 J, Ho laser rod temperature of 16℃, and repetition rate of 3 Hz.

trical signals. The signals show, in order from top to bottom, the relative timing of the flashlamp trigger, flashlamp visible output, Ho fluorescence near 1.8 μm, Ho fluorescence in the green wavelength range, normal mode oscillation of the Ho laser (without Q-switch), the RF drive signal to the A/O Q-switch, and the Q-switched Ho laser pulse. It should be noted that the signal obtained from the 1.8 μm Ho fluorescence is indicative of the measured 3.5 ms lifetime of this level and is similar to that reported previously.5,7) The strong green fluorescence is due to the $^5S_2$-$^5I_8$ transition in Ho.7) Figure 2(b) shows a more detailed pulse shape of the Q-switched Ho laser pulse.

The pulse energy and pulse width of the Q-switched laser pulse were found to be strongly dependent upon the delay time of the A/O Q-switch RF turn-off time. This is shown in **Fig. 3** which shows the measured pulse energy as a function of the delay time. The optimal delay time was found to be approximatly 630 μs for our experimental setup. Our laser had the following operational parameters: TEM_{00} mode, 12 mJ laser pulse energy, 120 ns pulse length, flashlamp input energy of 121 J/pulse, and Ho rod temperature of 16℃. An aperture of 3 mm was used to force the laser output into a TEM_{00} mode. The pulse energy for Q-switched multimode operation was 29 mJ/pulse and for normal oscillation (no Q-switch) was 37 mJ/pulse. Laser threshold was 96 J for the flashlamp energy. As seen in Fig. 3, the laser output is maximum at a pulse repetition frequency (PRF) of 3 Hz with a decrease seen at 4 Hz; a significant decrease was also observed at 5 Hz due to an increase in the thermal lens effect at the higher RPF values.

The Q-switched pulse width was also measured as a function of the Q-switch delay time and is shown in **Fig. 4.** As can be seen, the shortest pulse length occurs at the delay time for the highest output power which is as expected. It should be added that because the transfer of excitation in the laser rod involves the Cr and Tm ions also, the Ho population inversion can also occur at significant delay time.8) This long term excitation process can produce a secondary (or double) pulse which occurs much later in time affer the Q-switched pulse. In order to elliminate this double pulse, the RF drive to the Q-switch was turned "back-on" after approximately 1.5 μs at the end of the regular RF drive pulse. This is not shown in Fig. 2 for ease of clearity in explaining the relative timing of the Ho laser.

The output energy and pulse width of the Ho laser were also investigated as a function of the flashlamp input power and operating temperature of the Ho laser rod. **Figure 5** shows the measured

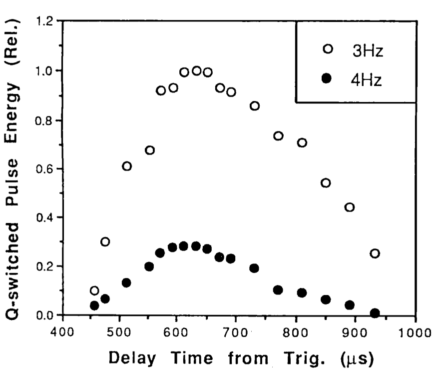

Fig. 3 Q-switched pulse energy as a function of the Q-switch delay time from the flashlamp trigger.

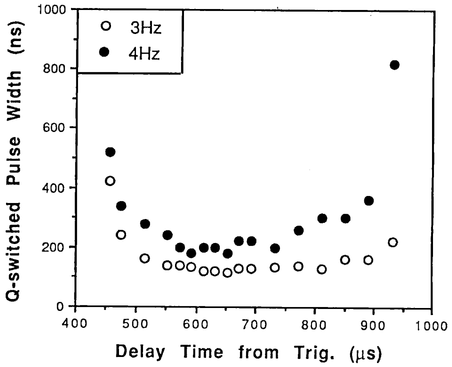

Fig. 4 Q-switched pulse width as a function of the delay time from the flashlamp trigger.

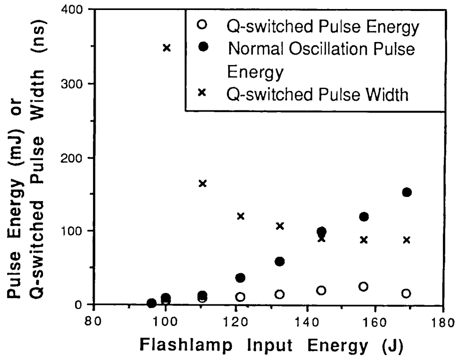

Fig. 5 Pulse energy (mJ) for the both normal oscillation and Q-switched operation, and the Q-switched pulse width (ns) as a function of flashlamp input energy.

laser output pulse energy for both normal oscillation and Q-switched operation, and the measured Q-switched pulse width. As seen in Fig. 5, at the higher flashlamp input levels, the TEM_{00} mode Q-switched laser pulse had a pulse energy of 25 mJ and a pulse width of 88 ns with a flashlamp input energy of 156 J. The normal oscillation pulse energy increased to nearly 150 mJ/pulse at the higher input levels but the Q-switched output power did not significantly increase. While this may be indicative of the relatively low saturation fluence of the Ho laser, it may be also due to losses in our A/O Q-switch. We are currently studying this more in order to improve the Q-switched output power.

Figure 6 shows the Q-switched pulse energy and pulse width as a function of the laser rod temperature. As can be seen, an operational temperature near 16℃ seems to optimize the output power of the Ho laser with a concurrent reduction in the laser pulse width. It may be added that, in general, the threshold energy of the Ho laser is decreased when the rod is cooled because the population of the lower state laser level of Ho is lowered.[9] The optimal temperature is dependent upon several experimental conditions, including the rod geometry, cooling design, related thermal aspects, heat load of the flashlamp, and laser energy extraction efficiency. In our experiments, the optimal temperature was found to be near 16℃, although this value will change slightly for different PRF and flashlamp input energy.

We have also studied the tunability of the Ho laser. Two uncoated glass etalons (0. 2 mm and 1. 0 mm thickness) were inserted in the Ho laser cavity between the output mirror and the laser rod. The measured tuning curve is shown in **Fig. 7** which indicates that the Ho laser can be tuned smoothly from 2. 081 μm to 2. 087 μm ; the linewidth of the laser was measured to be approximately 0. 1 nm. These tuning results are similar to our previously reported results.[3] It is informative to mention that the wavelength of the Ho : YSGG laser is similar, but not exactly the same, to that of the Ho : YAG laser. Recently, Henderson and Hale[10] have shown that the Ho : YAG laser operates on two closely spaced lines at 2. 090 μm and at 2. 097 μm, with tuning obtained from 2. 088 to 2. 098 μm.

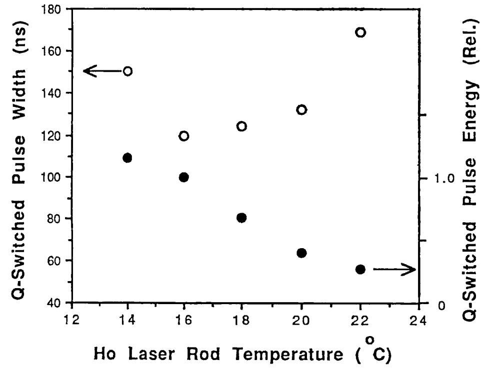

Fig. 6 Q-switched pulse energy and Q-switched pulse width as a function of the laser rod temperature.

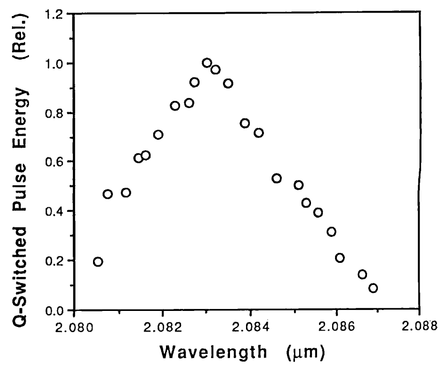

Fig. 7 Tuning curve of the Ho laser.

4. Conclusion

In this technical note, we have documented our studies of the operational characteristics of a flashlamp pumped A/O Q-switched Cr: Tm: Ho: YSGG laser operating on the 2. 1 μm Ho laser line. Typical operating parameters of the Q-switched laser were pulse energy of 25 mJ and a pulse width of 88 ns with a flashlamp input energy of 156 J, temperature of 16℃, and repetition rate of 3 Hz. The pulse energy was somewhat greater than that obtained previously using a spinning mirror Q-switch.[3] Continuous tuning of the Ho laser was also obtained over a range from 2. 081 μm to 2. 087 μm.

Our future plan is to injection seed our Ho laser in order to have it operate as a tunable single-frequency laser source. Such operation will permit it to be used in a Doppler lidar system as well as a differential-absorption lidar for atmospheric water vapor and CO_2 measurements.

Acknowlegement

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