Diode-pumped long-pulse-length Ho:Tm:YLiF$_4$ laser at 10 Hz

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Received September 22, 1994

An optical efficiency of 0.052 under normal mode operation for diode-pumped Ho:Tm:YLiF$_4$ at a pulse repetition frequency of 10 Hz has been achieved. Laser output energy of 130 mJ/pulse at 10-Hz operation. The laser pump head consists of three diode array systems placed between crossed polarizers, an extinction ratio of 1500:1 was measured with a He–Ne laser. A narrow spectral bandwidth is required so that accurate wind velocity measurements can be made. In turn, the long pulse length results from Fourier-transform limits on the narrow-spectral-bandwidth pulse. Long pulse lengths are required for the narrow, transform-limited bandwidths needed to measure wind velocity to ±1.0 m/s. For our experiments, a 42-mm-long diode-pumped laser rod with a 4-mm diameter was utilized. The laser pump head design, consisting of two sets of five laser diode arrays (LDA’s) placed symmetrically around the perimeter of the laser rod, is shown in Fig. 1. The 4-mm-diameter pump head is encased by a fused-silica glass flow tube with a 5-mm inner diameter and a 7-mm outer diameter, respectively. The laser rod is directly cooled by the flow of water. Because the O-ring seals occur on an unpumped section of the laser rod, minimal thermal stress on the laser rod will occur at the seals. The temperature of the coolant flow was maintained at 16°C in our experiments.
Nominal coolant flow rate around the laser rod was 1 L/min. This flow rate corresponds to laminar flow in our system. In total, 10 diode arrays were used to pump a 20-mm length of Ho:Tm:YLF. The LDA's were six-bar-stack devices with 300-W peak power. The pulse repetition frequency was varied from 1 to 10 Hz, and the current pulse length was 1 ms. We temperature tuned the LDA's by controlling the temperature of the circulating cooling water. A center wavelength of 0.792 μm was selected for optimum absorption of the pump light by the α-axis Ho:Tm:YLF laser rod.

A maximum optical-to-optical efficiency of 0.052, corresponding to 130 mJ of laser output energy for 2.526-J optical input energy, was achieved with a 0.90-reflecting output coupling mirror. The slope efficiencies and threshold energies were measured in a 50-cm-long standing-wave resonator composed of an 80-cm radius-of-curvature high-reflector and various flat output coupling mirrors. Results of these experiments at 10 Hz, with various output mirror reflectivities, are shown in Fig. 2. We did not obtain data at high pump energies for the 0.98- and 0.94-reflecting output mirrors so we could avoid optical damage that is due to high circulating fluences in the resonator. The slope efficiency is 0.144 for the 0.90 output coupling mirror and is 0.134 of the 0.94 output coupling mirror. Laser output wavelength was centered at 2.065 μm for various output coupling mirrors. These results obtained at a pulse repetition frequency of 10 Hz are comparable with the results previously reported for 1-Hz operation of Ho:Tm:YLF.12 The significant increase in pulse repetition frequency is attributed to pumping all the doped length of gain medium as well as to better extraction of heat from the laser rod. Higher efficiencies or higher pulse repetition frequency operation can be obtained by decreasing the temperature of coolant flow around the laser rod. The observed laser output was multitransverse mode for this resonator.

The efficiency of the diode-pumped Ho:Tm:YLF laser is limited by the available pump energy. Flash-lamp-pumped Ho:Tm:Cr:YAG lasers can have a comparable efficiency because they can be pumped by a factor of 2.0 over optical transparency. In addition, Cr is an efficient absorber of the flashlamp radiation, and the quantum efficiency can be high. In the diode-pumped Ho:Tm:YLF case, pumping is limited to a factor of 1.3 over optical transparency. Thus, even though the quantum efficiency can also be high for the diode-pumped case, the overall efficiency is comparable with that of flash-lamp-pumped Ho:Tm:Cr:YAG. Higher efficiencies should also be possible by closer coupling of the laser diode arrays to the laser rod.

We have obtained the requisite 600-ns-long Q-switched pulses by using a 4-m ring resonator in a figure-eight configuration. This ring resonator consists of two flat high reflectors, a 4.5-m radius-of-curvature high reflector, and a 0.82-reflecting output coupler. An acousto-optic Q switch made of water-free fused silica having Brewster faces was used for Q-switched operation. In our experiments the acousto-optic Q switch was adjusted for a particular pump energy to produce unidirectional operation of this ring resonator. The Q-switching approach used in a ring resonator permits longer photon lifetimes, yielding longer pulse lengths, and, because spatial hole burning is eliminated, narrow-frequency laser outputs are possible. We measured laser output energies and pulse lengths of Q-switched pulses by varying the input optical pump energies for various pulse repetition frequencies. Pulse lengths were measured with a fast-response gold-doped germanium detector.

We have achieved maximum laser output energies of 30 mJ in a single Q-switched TEM00-mode pulse with a 590-ns pulse length for an input energy of 3 J, corresponding to a 0.01 optical-to-optical efficiency. Results of this study for a pulse repetition frequency of 10 Hz are shown in Fig. 3. We achieved unidirectional operation by adjusting the Q switch around Bragg angle, as reported in earlier studies by Clarkson et al.13 For the results shown in Fig. 3, the acousto-optic Q switch was adjusted to produce unidirectional operation with a laser output energy of 30 mJ. At energies below 15 mJ the ring laser operated in both directions.

![Fig. 1. Design of the water-cooled pump head.](image1)

![Fig. 2. Slope efficiencies and threshold energies for a 50-cm-long resonator at a pulse repetition frequency of 10 Hz and a coolant flow temperature of 16 °C.](image2)
absorption lidar measurements. Experiments are in the output laser wavelength from 2.052 to 2.066 μm. By inserting an etalon into the resonator we were able to vary the resolution limit of our detection system. By inserting an etalon into the resonator we were able to vary the resolution limit of our detection system. By inserting an etalon into the resonator we were able to vary the resolution limit of our detection system. By inserting an etalon into the resonator we were able to vary

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The laser output wavelength was centered at 2.052 μm, with a FWHM of 220 pm, which is the same resonator conditions are shown in Fig. 4. The beam quality of our laser output is 1.4 times diffraction limited, and the variation of the beam quality as a function of input average power is less than 0.1. This observation is in agreement with results obtained for Nd:YLiF4 by Murray.14

The laser output wavelength was centered at 2.052 μm, with a FWHM of 220 pm, which is the resolution limit of our detection system. By inserting an etalon into the resonator we were able to vary the output laser wavelength from 2.052 to 2.066 μm. Such a laser system would be useful for differential absorption lidar measurements. Experiments are in progress on injection seeding of this laser to achieve narrow optical bandwidths needed for velocity resolution.

For the water-cooled laser system no parasitic lasing was observed, as expected, even at the highest pump energies available. Parasitic lasing can occur on total internal reflection modes of the laser rod. Lasing on these modes reduces the laser output energies and thus the efficiency of the laser system. Parasitic lasing will make it impossible to increase the stored energy, which limits efficiency of the laser system. Once parasitic lasing starts, all further pump energy is converted into parasitic lasing modes and therefore is not available in the single Q-switched pulses.

In conclusion, we have shown an optical-to-optical efficiency of 0.052 for normal mode operation of a diode-pumped Ho:Ym:YLF laser at a pulse repetition frequency of 10 Hz. Maximum output energy of 30 mJ was obtained in single Q-switched pulses with 590-ns pulse lengths corresponding to an optical-to-optical efficiency of 0.01. We achieved operation of this laser system at 10 Hz by using a diffusion-bonded birefringent laser rod consisting of doped and undoped pieces of YLF.

We gratefully acknowledge cooperation and support from H. Meissner of ONYX Optics with the diffusion bonding of the YLF material.

References
