High-average-power, conductively cooled Tm,Ho:YLF laser for Doppler wind lidar

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Abstract: A conductively cooled Tm,Ho:YLF laser is one of the most promising laser sources for a spaceborne Doppler wind lidar. In this study, high-average-power operation of the conductively cooled Tm,Ho:YLF laser was demonstrated at a crystal temperature of −80 °C. At a pulse repetition frequency of 70 Hz, a Q-switched pulse energy of 104 mJ was obtained. This corresponds to an average output power of 7.28 W, which is the highest average power for a 100-mJ-class Q-switched Tm,Ho:YLF laser oscillator with conductive cooling. The maximum output energy reached 125 mJ at 50 Hz. Based on these results, an optical design of a master oscillator and power amplifier system operating at −40 °C was investigated to reduce the power consumption of the laser transmitter.

Keywords: Lidar transmitters, 2-micron lasers, conductive cooling, high-power lasers.

1. Introduction

A conductively cooled, Q-switched Tm,Ho:YLF laser is suitable for use as a transmitter in a spaceborne Doppler wind lidar (DWL). Recently, a super low altitude test satellite was successfully launched by the Japan Aerospace Exploration Agency in December, 2017 [1]. Although it moderates the requirements for the DWL transmitter, a 100-mJ-class laser source is still required [2]. For DWL transmitters, not only single-longitudinal-mode operation but also high-average-power operation is needed because the figure of merit (FOM) of the DWL system is defined as a product of the pulse energy, the square root of the pulse repetition frequency (PRF), and the telescope diameter. Under the same telescope condition, the FOM depends only on the product of the pulse energy and the square root of the PRF. Conductively cooled Tm,Ho:YLF lasers for spaceborne DWL applications have been developed at the National Institute of Information and Communications Technology. In our previous work, an average output power up to 2.4 W has been achieved at a crystal temperature of −80 °C [3, 4]. However, further power scaling of the laser is required for the DWL measurements from a super low altitude satellite (~220 km). Our goal is to develop the Tm,Ho:YLF laser transmitter capable of producing a pulse energy of 125 mJ at a PRF of 30 Hz, corresponding to an average output power of 3.75 W. In addition, the higher operating temperature (~ −40 °C) is preferable to reduce the power consumption of the cooling system. In this paper, we report on high-average-power operation of the Q-switched Tm,Ho:YLF laser at −80 °C. Based on the results of laser experiments and numerical simulations, a DWL transmitter design for high-power operation at −40 °C is also investigated.

2. Experimental setup

The YLF laser rod codoped with 4% Tm and 0.4% Ho was 4 mm in diameter and 33 mm in length was mounted into three copper heat-sink blocks using 50-µm-thick indium foils for better thermal contact between the laser rod and the heat sink. The pump source was a three-stacked laser diode (LD) with a pitch of 400 µm and was temperature-tuned to the 792 nm absorption peak of Tm,Ho:YLF. The pump module
consisted of a set of three LDs arranging side by side and a quartz light guide plate with an end-face dimension of 33.7 mm × 1.2 mm. Three pump modules were arranged 120° apart around the laser rod. The Cu heat sinks for the laser rod were liquid-cooled by circulating Fluorinert coolant. The laser head was placed inside a vacuum chamber to prevent condensation and frost. The resonator configuration of the Q-switched Tm,Ho:YLF laser is shown in Fig. 1. A 3.86-m-long ring resonator was used in our experiment. The flat output coupler (OC) had a reflectivity of 61% or 74% at 2050 nm. The resonator consisted of the OC and three flat mirrors having a high-reflection coating for a wavelength of 2050 nm. A crystal-quartz acousto-optic (AO) Q-switch was used as a Q-switch element. Two convex lenses with a focal length of 3 m (L1, L2) were inserted into the resonator for the compensation of the negative thermal lens in the Tm,Ho:YLF rod. When the focal length of thermal lensing is 1 m or longer, the resonator is always stable, and the TEM_{00} mode radius at the laser rod remains almost constant around 1 mm. This leads to a good overlap between the cavity mode and the central pumped region with a diameter of approximately 2 mm.

Figure 1. Resonator configuration of the Q-switched Tm,Ho:YLF laser.

3. Experimental results

The lasing characteristics in both normal- and Q-switched-mode operations were measured at 50 and 70 Hz. The results are shown in Fig. 2. When the laser was operated in normal mode at 50 Hz with a 0.8 ms pump pulse, the threshold pump energy and the slope efficiency were 0.63 J and 16.7%, respectively. The maximum normal-mode pulse energy of 200 mJ was obtained for a pump energy of 1.85 J. The same performance as in normal-mode operation was obtained in Q-switched-mode operation for a pump energy lower than 1 J. However, the slope efficiency in Q-switched-mode operation decreased as the pump power

Figure 2. Pulse energy and pulse width of the Tm,Ho:YLF laser as a function of pump energy. The laser was operated (a) at 50 Hz with a 0.8 ms pump pulse and (b) at 70 Hz with a 0.6 ms pump pulse.
increased under intense pumping. This can be explained by the decrease in the fractional population of the Ho upper-laser manifold in the coupled Tm-Ho system resulting from the depletion of the Ho lower-laser manifold due to the high pumping density. Nevertheless, a Q-switched pulse energy of 125 mJ was achieved at 50 Hz, corresponding to an average output power of 6.25 W. The pulse width was then 80 ns. As can be seen in Figs. 2(a) and 2(b), the threshold pump energy at 70 Hz was lower than that at 50 Hz. The reason for the lower threshold at 70 Hz is that the short pumping interval leads to a large residual population in the Ho upper-laser manifold for the next pump pulse. The maximum average output power at 70 Hz reached 7.28 W [5]. While the $M^2$ value increased with increasing average pump power, it was not higher than 1.5 even at the maximum average pump power.

In order to investigate the contribution of the residual population in the Ho upper-laser manifold to the next pump pulse, pulse energies and pulse widths were measured for several different PRFs. Fig. 3 shows the experimental and calculated results for a pump energy of 1.45 J. Numerical simulations were performed by using a rate-equation model [6]. The additional pump energy due to the residual population after lasing was estimated by taking into account the second quasi-thermal equilibrium between the Tm and Ho upper-laser manifolds and the decay of the Ho upper-laser-manifold population. The lifetime of the Ho upper-laser manifold was assumed to be 15 ms. Thermal effects are not included in the calculation. An obvious enhancement of the output energy appeared in the calculated curves at PRFs higher than 20 Hz. This indicates that there is a trade-off between the additional pump energy and the temperature rise at high PRFs. However, the measured output energy decreased at PRFs higher than 50 Hz so that the PRF range of 30 to 50 Hz might be optimal choice in our system. The Q-switched-mode operation at $-40 \, ^\circ\text{C}$ was also demonstrated at a PRF of 30 Hz, as shown in Fig. 3. The output energy decreased from 103 to 45 mJ as the temperature of the laser rod was increased from $-80$ to $-40 \, ^\circ\text{C}$. Although the high output energy was obtained at $-80 \, ^\circ\text{C}$, the pulse width was one-half of our target. On the other hand, the pulse width observed at $-40 \, ^\circ\text{C}$ fulfilled the requirement of the DWL system. Therefore, a master oscillator and power amplifier (MOPA) is a promising candidate for the laser transmitter operating at $-40 \, ^\circ\text{C}$.

4. Comparison of oscillator and MOPA

Since the experimental results shown in Fig. 3 were in reasonable agreement with the calculated results, the MOPA system operating at $-40 \, ^\circ\text{C}$ was investigated with numerical simulations. Figs. 4(a) and 4(b) show the results of simulations for the laser oscillator with two laser heads and the MOPA, respectively. It is
assumed that the MOPA system consists of the single laser-head oscillator and the single laser-head 2-pass amplifier. Pulse energies and pulse widths were calculated for different amplifier pump energies as a function of the oscillator pump energy. As shown in Fig. 4(a), the pump energy required for 125-mJ output was calculated to be 3.1 J, and the pulse width of the oscillator is shorter than 80 ns at this output level. On the other hand, an output energy of 125 mJ can be obtained in the MOPA with total pump energies of 3.1−3.2 J. In this condition, the pulse width is longer than 160 ns. This result supports the superiority of the MOPA system.

5. Conclusion

We have demonstrated a conductively cooled Q-switched Tm,Ho:YLF laser operating at −80 °C with an average output power higher than 7 W. To reduce the power consumption of the cooling system, a design of the laser transmitter operating at −40 °C was investigated. As a result, we found that a MOPA system is a promising candidate for a 3.75-W DWL transmitter operating at −40 °C.

6. References


