

One-Joule-Per-Pulse Q-switched 2-micron solid state laser

Jirong Yu, Bo C. Trieu, Ed A. Modlin, Upendra N. Singh and Michael J. Kavaya
NASA Langley Research Center, MS 468, Hampton, VA 23681

Songsheng Chen, Yingxin Bai and Pual J. Petzar
Science Applications International Corporation, One Enterprise Parkway, Suite 300,
Hampton, VA 23666-5845

Mulugeta Petros
Science and Technology Corporation, 10 Basil Sawyer Drive, Hampton, VA 23666

Abstract: Q-switched output of 1.1 J per pulse at 2-micron wavelength has been achieved in a diode pumped Ho:Tm:LuLF laser using a side-pumped rod configuration in a Master-Oscillator-Power-Amplifier (MOPA) architecture. This is the first time that a 2-micron laser has broken the Joule per pulse barrier for Q-switched operation. The total system efficiency reaches 5% and 6.2% for single and double pulse operation, respectively. The system produces excellent 1.4 times of transform limited beam quality.

OCIS codes: (140.3580) Laser, solid state; (140.3480) Lasers, diode-pumped

Two-micron, pulsed, coherent-detection lidar systems provide carbon dioxide vertical profiles and tropospheric wind profiles with high measurement precision.^{1,2} The key component in these lidar systems is a reliable, high energy and efficient 2-micron laser. The laser has to be injection seeded and frequency controlled to meet the single frequency requirement for these measurements as well. For a space-borne coherent lidar system, joule level output energy is required to be able to accurately measure the global wind fields. Although theoretical simulation predicted that Ho and Tm based lasers would have generated Joule energy decades ago,³ not such a high energy laser has been reported.

Recently, significant advancements in the 2-micron laser development have been made in terms of high energy demonstrations. A 125 mJ injection seeded 2-micron Ho:Tm:YLF oscillator at room temperature was developed in 1998.⁴ A 400mJ Q-switched 2-micron laser system using a conductively cooled laser pump module was reported in 2004.⁵ A 600 mJ Q-switched diode-pumped Tm:Ho:LuLF using a MOPA system at double pulse format was published in 2003.⁶ Last year, a Joule level 2-micron laser MOPA system was reported, but it was operated in double-pulse format.⁷ This paper describes, for the first time, a one-joule-per-pulse Q-switched 2-micron laser system, which makes a significant milestone in the high energy 2-micron laser development.

The MOPA 2-micron laser system comprises an oscillator, a preamplifier and two power amplifiers as show in Figure 1. The MOPA system is a typical way to achieve high energy, and at the same time to preserve good beam quality required by the nature of coherent lidars. The laser and amplifiers are all designed in side-pumped rod

configuration, pumped by conductively cooled A packaged GaAlAs diode laser arrays. The efficiency of the diode laser arrays is in the range of 38% to 44%. The symmetry afforded with side-pumped rod geometry helps to produce a high quality, circularly symmetric Gaussian beam output. The laser oscillator was pumped by two banks of three, radially arranged, 792nm laser diode arrays, each capable of producing 600 mJ of optical power for a nominal total of 3.6 J of 1 ms pulses. The laser oscillator and amplifier modules are in monolithic design. The diode arrays were directly mounted on aluminum modules, cooled by flowing water at 15°C. The amplifier modules are similar to the oscillator module design, except using four banks of three, radially arranged laser pump diode arrays with total nominal pump energy of 7.2J of 1ms pulses. The preamplifier module is exactly the same as the oscillator module. The gain medium of the laser system is Tm:Ho:LuLF crystal with 6% Thulium and 0.5% Holmium doping concentration. A detail study of the Tm:Ho codoped crystals of YLF and the isomorphs LuLF and GdLF revealed that small changes in the thermal population of the lower laser level in ground state terminated lasers can significantly alter the laser performance.⁸ The larger host ion size of Lu leads to larger crystal fields and, as a result, larger crystal field splitting of lanthanide series ions. Thus, the LuLF host crystals provide better laser performance compared with YLF or GdLF based lasers.⁹ The dimensions of these laser crystal rods are 4 mm in diameter and 20 mm in length, and 5mm in diameter and 40mm in length for oscillator and amplifiers, respectively. The laser rods are directly cooled by running water. The pump diode arrays and the laser crystal rods are cooled in different loop, so the temperatures of diodes and rods can be independently controlled. The system is operated at a repetition rate of 2 Hz.

The oscillator uses a stable ring resonator configuration to obtain a near Gaussian spatial profile beam. A stable resonator design is less sensitive to external vibrations and other mechanical perturbations in terms of laser performance. This is clearly desirable in an untended vibration and temperature-cycle prone environment. An output coupler with 66% reflectivity, as a compromise between the output energy, fluence inside the resonator and output pulse length, is used. The total resonator length for this laser is 2.8 meters. The large resonator length is a simple way to obtain the long laser pulse width that is desirable to achieve a Fourier transform limited narrow linewidth. An acoustic-optic Q-switch provides single or double Q-switched pulses. To obtain single longitudinal mode oscillation, injection seeding is required.¹⁰ The ramp and firing technique was previously implemented for such a 2-micron laser.⁴ By injection seeding, not only a single longitudinal mode oscillator was obtained, unidirectional output of the ring resonator was achieved as well. However, for simplifying this experiment, the injection seeding is not implemented. A retro reflector is used to obtain unidirectional output.

The oscillator output passes through a half wave plate and Thin Film Polarization (TFP) combination, so one can control the energy without changing the beam dimension simply by rotating the half wave plate. It helps to investigate the performance of the MOPA system, but can be eliminated to reduce the number of optical components in the system. The output of the oscillator is first amplified by a preamplifier and then double passes the amplifier one. Amplifier two is set up for single pass due to the high fluence optical

damage concerns. The rest of the half plates in the system are used to align the beam polarization to the c axis of the birefringent LuLF crystal for maximizing the amplification gains.

2-micron Ho lasers are quasi four level lasers, so low temperature of the laser gain medium helps to reduce the threshold and to increase the slope efficiency. The coolant temperature can not be lower than 8°C in the experiment, limited by the dew point constraint. Fig.2 depicts the oscillator performances for long pulse, single Q-switch and double Q-switch operations at a laser rod coolant temperature of 8°C. The laser slope efficiencies for the three operation formats are 16.5%, 11.9%, and 14.3%, respectively. The oscillator is capable of producing 150 mJ. However, due to the concern of optical damage by high intracavity fluence, the output is lowered to a 100mJ level by reducing the pump diode current. The width of the output pulse is longer at the derated optical pump power, which is also beneficial for higher amplification gain in the amplifier stages. Derating the pump diode power helps to extend the lifetime of the pump diodes as well. The full width half maximum of the oscillator pulse width is measured at 187 ns. This probe beam is amplified through the following amplifier stages.

The preamplifier increases the laser energy to 187 mJ. To maximize the extracted energy, the two amplifiers shall be operated near saturation. Under three-side pumping geometry, the gain profile peaked at the rod center and lower at edges. Some portion of the area around the edge of the rod where it did not directly face the diodes may not even reach the threshold of the population inversion, resulting in net loss in these areas. Thus, the optimal mode matching between the probe beam and the pump volume is an important factor. Mode matching is realized by selecting the radius of curvatures of the reflect mirrors between the amplifier stages. Fig. 3 shows the optical gains of amplifier one at 172mJ input energy. For a single pass, a gain of 2.14 is obtained at the maximum pump power for amplifier one. By double passing the amplifier, total gain of 3.20 is achieved. It represents 50% improvement compared to the single pass amplification. In the double pass regime, temporal overlap significantly affects the gain, especially for the 187ns long pulse. The fact that the gain of the double pass amplification is not twice of the single pass amplification indicates gain saturation of amplifier one.

The Frantz-Nodvik equation was used to simulate the performance of amplifier one for both the single and double pass amplification¹¹

$$d(E(z, t)/E_s)/dz = g_0[1-\exp(-E(z, t)/ E_s)] - \alpha_o E(z, t) \quad (1)$$

where the g_0 is the small signal gain coefficient, E_s is the saturation intensity, and the α_o is the unsaturable loss. The small signal gain coefficient, g_0 , and saturation intensity, E_s , may be measured and derived from the gain measurements of the amplifier. The calculated data agrees with the experiment result with a small signal gain coefficient of 0.26 cm^{-1} and saturation energy of 0.492J.

Fig. 4 shows the MOPA system performance for normal mode, single Q-switch and double pulse Q-switch output. For total MOPA system pump energy of ~21.9J, 1.1 J

single Q-switched output energy is achieved. It is the first time that the energy of a single Q-switched solid state 2-micron Ho laser is above the one-joule-per-pulse barrier. The optical to optical conversion efficiency is 5%. In the double pulse Q-switch operation, the total output energy reaches 1.35 J, representing an optical to optical conversion efficiency of ~6.2 %. In double pulse operation, the second pulse energy comes from the free repopulating energy transfer process between the Tm and Ho ions after the Ho energy extraction by the first pulse.¹²

This 2-micron laser system provides nearly transform limited beam quality. Table one listed the beam quality for each stage of the MOPA system. The beam quality of the MOPA system is characterized by scanning knife edge technique at each of the stages in the system. A diffraction limited 500 mm focal lens is used in the measurements. Approximately 11 planes centered on the waist through the laser beam path after the focal lens are sampled to obtain beam diameters. The knife edge scan is controlled by Labview and the data is automatically stored and processed by computer. The curve fitting then applied to the data points with fitting parameter R^2 value of at least 0.97. The beam quality is directly derived from the fitting parameters. Except the last amplifier, the beam qualities for oscillator, preamplifier and double pass amplifier one are excellent at the value of 1.1x transform limited. Even at the last amplifier stage, the beam quality is 1.4x transform limited.

In summary, a larger than one-joule-per-pulse, diode pumped, Q-switched 2-micron laser has been successfully demonstrated. It represents, for the first time, that a 2-micron solid-state laser can produce Joule level energy in a single Q-switched pulse. This 2-micron MOPA system provides excellent beam quality as well. This high energy 2-micron laser demonstration is one step closer for developing a space-borne coherent Doppler wind lidar with the required energy.

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Figure Captions:

Fig. 1 Diode pumped 2-micron Ho:Tm:LuLF MOPA system diagram

Fig. 2 Oscillator output performance for normal mode, single Q-switch, and double Q-switch pulses

Fig. 3 Single and double pass gain for Amplifier one

Fig. 4 The Ho:Tm:LuLF MOPA system output energy performance

Figure 1 Yu et al, Opt. Lett

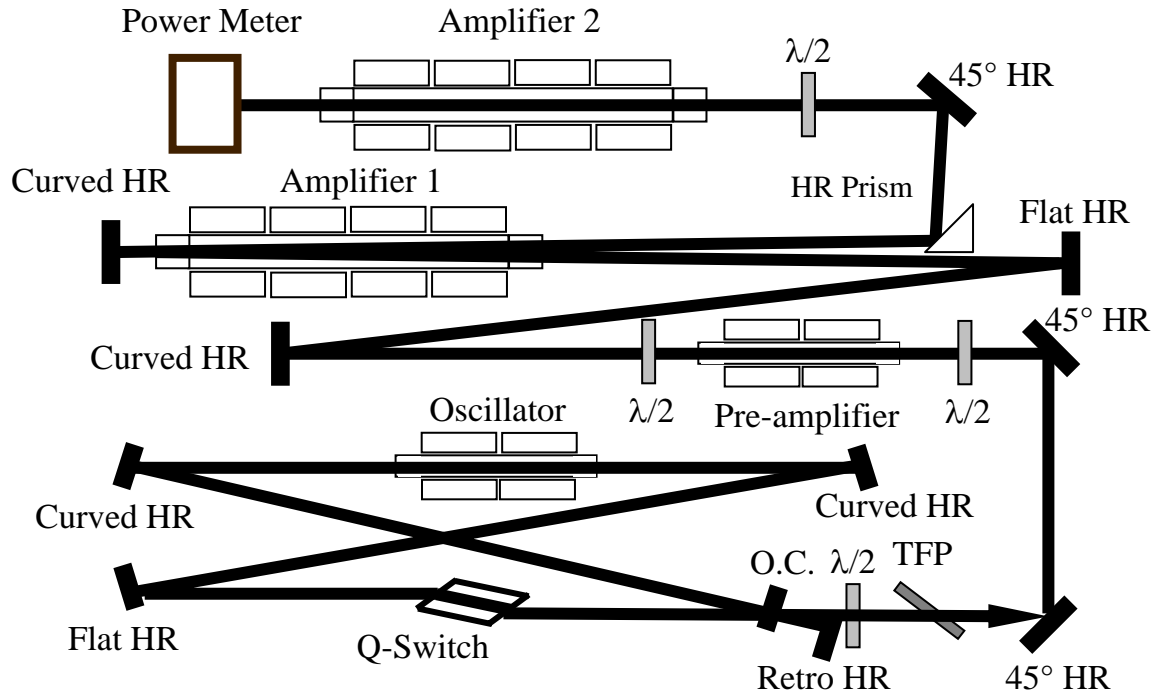


Figure 2 Yu et al, Opt. Lett

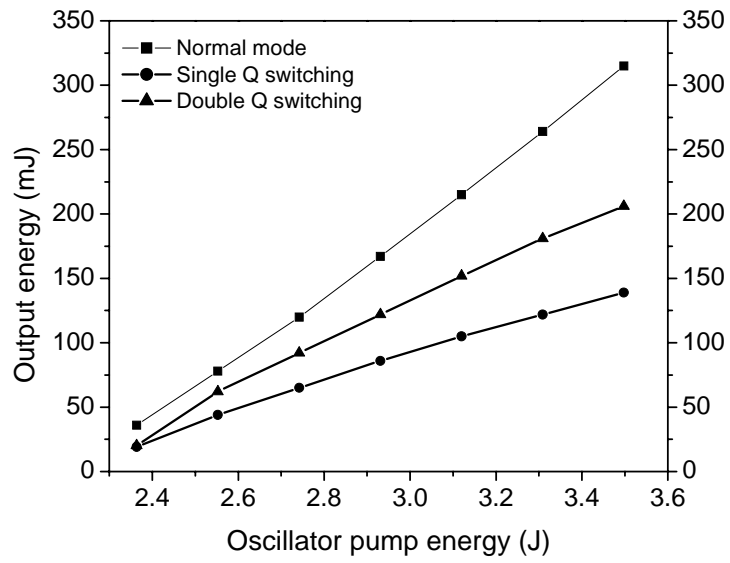


Figure 3 Yu et al, Opt. Lett

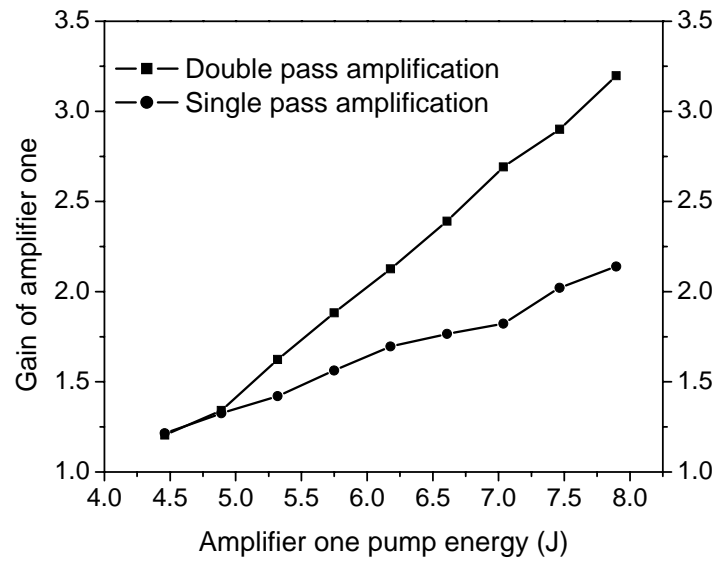


Figure 4 Yu et al, Opt. Lett

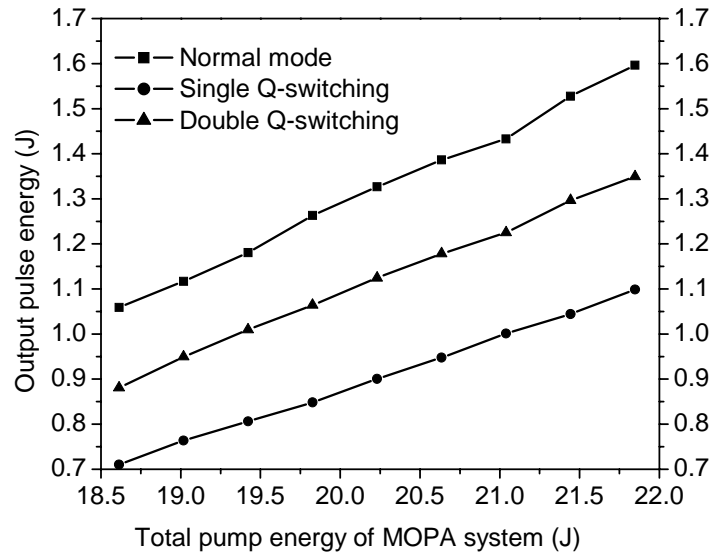


Table 1 Beam quality at the each stage of the MOPA system

M^2	OSC	PreAmp.	Amp. 1	Amp. 2
X axis	1.14	1.09	1.09	1.44
Y axis	1.06	1.11	1.22	1.45
Aver.	1.10	1.10	1.16	1.45