A compact solid state laser
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ABSTRACT

A compact laser producing a green wavelength with a volume of < 8 cm$^3$ and a weight of < 80 g finds application in many fields from military to space based. Q-Peak has designed and built a small solid-state laser that produces 1 mJ of energy per-pulse at a 1-20 Hz repetition rate. The laser is passively Q-switched using a Cr$^{4+}$:YAG saturable absorber to generate pulses < 10 ns. A KTP nonlinear crystal doubles the frequency to generate light at 523 nm. The laser is side-pumped by a single bar diode laser using a unique pump cavity to homogenize the pump intensity in the laser rod. The non-linear components can easily be modified to change the output wavelength from UV to mid IR.

**Keywords:** Compact, miniature solid-state lasers, passively Q-switched, side pumped, frequency conversion

1. INTRODUCTION

A laser operating in the green wavelength region is important for molecular analysis using Raman spectroscopy, mapping ocean tomography using LIDAR, scribing semiconductor wafers etc. A compact, lightweight, and efficient laser is essential for space based applications and for man portable instruments where there are constraints on size weight and power (SWaP). When mounted on a rover arm, this compact laser is designed to perform elemental analysis on samples by means of context imaging. Raman and laser induced breakdown (LIB) spectroscopy. When integrated into an instrument such as a range finder, the small size and lightweight minimize the kit size for individual soldiers. The compact laser is characterized by the following specifications: energy, 1 mJ; pulse duration, < 10 ns; wavelength, 523 nm: beam quality, TEM$_{00}$; repetition rate, 1-20 Hz; volume, < 8 cm$^3$; and weight, < 80 g. There are several commercial lasers such as micro-chip lasers and fiber based lasers with low energy, ~$\mu$J per pulse at high repetition rates available at near IR wavelengths. Micro-chip lasers have demonstrated 250-$\mu$J of energy at 1064 nm with pulsewidths in the range of 100s of ps. However, scaling the energy to the mJ level has not yet been demonstrated. In the present design, Nd:YLF serves as the laser material instead of the more common material, Nd:YAG. Nd:YLF lasers produce higher energy per pulse at repetition rates < 1 kHz based on the longer upper state lifetime. The pump absorption in the laser crystal has been optimized by designing a unique pump head channel and a specific crystal shape and size. This geometry provided manufacturing tolerance for slight misalignment and temperature variations. The laser is side-pumped by a semiconductor laser and passively Q-switched by a Cr$^{4+}$:YAG saturable absorber. An intra-cavity KTP crystal in the laser resonator doubles the laser frequency to generate green light at 523 nm.

2. LASER

The Nd:YLF laser crystal is side pumped by a single-bar diode laser operating at 792 nm. A cross-sectional view of the laser rod with pump power distribution is shown in Figure 1. The pump power distribution inside the laser crystal was modeled using ray tracing software, TracePro, to map the distribution of pump energy in the laser rod. As shown, the cross-section of the laser rod is not circular. The flat entrance surface is coated with an antireflection coating at the pump wavelength. Also the flat section breaks the circular symmetry which might have supported whispering gallery parasitic modes. Polarization of the pump diode laser is parallel to the c-axis of laser crystal for pi absorption providing maximum absorption efficiency in Nd:YLF. In Figure 1, the c-axis of the laser crystal is parallel to the flat cut. Residual pump light is reflected back through the laser crystal by putting a high reflection coating at the back side of the crystal. If we assume an average absorption coefficient of 10 cm$^{-1}$, then the percentage of pump light absorbed in a single pass is 78 % and in a double pass through the crystal is 95 %.

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In the design, the pump light is directly coupled into the laser rod with no intervening optics. The lack of a micro-lens to shape the pump beam is advantageous in many aspects such as alignment insensitivity and thermo-mechanical insensitivity. A Gaussian energy distribution of the pump light is assumed in the plane of fast axis divergence that is in the direction of the flat line on the rod cross-section. The unique pump cavity homogenizes the pump energy and deposits it uniformly in the laser crystal, especially in the region where the laser beam is extracted. The position of the laser beam is shown as a circle superimposed on the pump distribution and fluorescence image in Figure 1. The pump laser is directly bonded to the laser housing making sure to electrically isolate the cathode and anode while maintaining good thermal conductivity between pump diode and laser housing. The laser rod is mounted without introducing mechanical stress and provides high thermal conductivity between the laser crystal and the housing. The purpose of this design is to make a compact and efficient laser which is extremely robust, and easy to assemble and align.

The laser is operated at 1047 nm and is naturally linearly polarized parallel to the c-axis of the crystal. Figure 2 shows a schematic of the laser resonator. The laser is passively Q-switched by a Cr$^{4+}$:YAG crystal. The outer surface of the Cr$^{4+}$:YAG is polished to a concave surface and coated with a high reflector at 1047 nm and 523 nm. A type II KTP crystal is placed inside the resonator to generate green light at 523 nm. The outer surface of the KTP crystal is polished to a convex surface and coated with a high reflector at both 1047 and 523 nm. The concave-convex laser resonator is operated near the edge of stability in order to obtain a large fundamental mode with a radius of 0.5 mm. A dichroic beam splitter that reflects 523 nm and transmits 1047 nm is placed inside the resonator to provide the output coupling for the laser. A CAD drawing of the laser head with dimensions is shown in Figure 3a. Connection to the pump diode laser is by two electrical pins as shown in Figure 3a. A photograph of the laser head without the cover is shown in Figure 3b.
3. POWER SUPPLY

An external driver, shown in Figure 4, generates the required current pulse to power the pump diode laser. Dimensions of the driver are $5 \times 1.7 \times 2.5 \text{ cm}^3$ and the weight is 17 g. At room temperature, without any active temperature control, the laser can be operated from single shot to a 20 Hz pulse repetition rate. This is limited by the driver design’s limiting repetition rate. If a different driver is used, then the laser can be operated up to 500 Hz with a thermo-electric cooler mounted at the bottom of the laser head. For a complete standalone laser, a power supply with safety features compliant to Center for Devices and Radiological Health (CDRH) regulations has been designed and can be integrated into customer systems. Dimensions and weight of the power supply are $11.2 \times 6.5 \times 4 \text{ cm}^3$ and $\sim 300$ g respectively. It operates from a 5 V battery.
4. RESULTS

A typical laser beam profile is shown in Figure 5a and a typical temporal profile is shown in Figure 5b. $M^2$ of the laser beam is 1.16. The laser pulse width at 1047 nm is ~10 ns. We measured the pulse-to-pulse timing jitter to be on the order of 1 µs which is an inherent property of passively Q-switched lasers. The energy per pulse is 1 mJ at 523 nm. The optical-to-optical efficiency is 10%.

Initial environmental tests have been conducted on the laser beginning with random vibration testing. The vibration was random from 2 - 2000 Hz at a power spectral density (PSD) of 0.05g²/Hz. The root mean square acceleration (Grms) was 10 which mimics launch conditions. The laser was subjected to this vibration for an hour on each axis for a total of 3 hours. Two acceleration monitors were installed; one on the shaker table and one on the laser. Figure 6 shows the response spectrum of each monitor in three directions. Laser performance was verified following the 3 hours of vibration (1 hr each axis). Figure 7 shows the pulse format and beam quality after the laser was subjected to vibration test. An hour of vibration at 10 Grms is an extremely harsh condition, exceeding actual launch conditions significantly in the temporal regime. However, subjecting the laser to such extreme conditions tests the limit of the laser performance. The fact that the laser still operated after three hours of vibration is proof of the design stability in tolerating induced mechanical misalignment.

The temperature of the laser was varied by putting a thermo-electric cooler (TEC) under the laser and measuring the temperature at the bottom of the laser enclosure. The measured average output power of the laser remained stable as a function of temperature. We calculated energy per pulse and the data is shown in Figure 8. Output power varied < 5% within the temperature range from 15 °C to 35 °C.
(a) Random vibration spectrum. ‘X’ axis, in the direction of laser output. Along the 18 mm dimension.

(b) ‘Y’ axis, in the direction of resonator length. Along the 34 mm dimension.

(c) ‘Z’ axis, perpendicular to the laser output and resonator length. Along 13 mm dimension.

Figure 6. Vibration spectrum as recorded by the sensor mounted on the shaker table and on the laser in different directions.

Figure 7. Laser performance after one hour of vibration each along of three directions. Left: Pulse width of the laser. Right: Beam quality of the laser.

Figure 8. Output energy per pulse as a function of temperature.
5. FUTURE

An alternative next generation laser packages with a smaller footprint, < 4 cm³ in volume and < 26 g in weight has also been developed without changing any of the current optics. Figure 9a shows the new design. The laser head is a cylinder 1.5 cm in diameter and 2.5 cm in length. Figure 9b shows the layout of the optics inside the housing. This same basic structure can be adapted for operation at different wavelengths; for example the second harmonic generator can be replaced with an optical parametric oscillator (OPO) to produce an eyesafe wavelength of ~ 1500 nm. A fourth harmonic generator can be added to produce UV wavelengths of ~ 262 nm. For operation at 1047 nm, the nonlinear crystal was removed and the package is even smaller with a 1.5 cm diameter and 1.4 cm length. Smaller and lighter packages are beneficial to space applications as well as unmanned vehicle exploration.

![Figure 9. CAD drawing of the new laser design. (a) cover on and (b) cover removed to show inside components. Dimensions are 1.5 cm diameter and 2.5 cm long. (c) CAD design for a laser operating near 1 micron wavelength. Dimensions are 1.5 cm diameter and 1.4 cm long.](image)

6. CONCLUSIONS

Q-Peak has built a compact, rugged, Q-switched, side-pumped Nd:YLF laser for space-based applications. The small laser produces 1-mJ of energy per pulse at 523 nm. The pulse width of the laser is ~10 ns. The laser can be operated from single shot to a 20-Hz repetition rate. Novel features of this laser are its compactness, ease of assembly and alignment, and overall electrical to optical efficiency. The pump head is uniquely designed to obtain a uniform deposition of pump energy in the laser rod for optimum extraction efficiency. A light channel between the pump diode and the laser crystal homogenizes the pump light making the position of the laser rod with respect to the pump diode highly insensitive. Since the relative position of diode and crystal is not critical, the assembly of these components in the pump head is particularly easy and does not require skilled labor during assembly. This will result in significant cost savings on assembly for volume production in the future.

Advantages of this laser are the smaller volume, lighter weight, and lower required power for operation. Another advantage is the modular form factor of the units. If a certain mission requires more power, an additional amplifier stage can easily be integrated into the same architecture. If other wavelengths such as IR, eye-safe and/or UV are required, alternative nonlinear crystals can be substituted into the assembly without change in the basic design.

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REFERENCE