1.34 µm $Nd:YVO_4$ laser passively q-switched by V:YAG and optimized for LIDAR

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ABSTRACT

$Nd:YVO_4$ has a high-gain transition at 1.34 µm. It can be q-switched by the saturable absorber Vanadium:YAG, which has quick recovery, enabling repetition rates above 1 MHz. I demonstrated a 1.34 µm laser for LIDAR with 1.08 nsec pulse duration, 24 kHz repetition rate and 1.75 kW peak power, and in another configuration, 4.8 nsec pulse duration, 1.82 MHz repetition rate and 68 W peak power. Several intermediate cases are described as well. These lasers have part-for-part correspondence with green pointer lasers sold for under $5 which are the size of a penlight. The eye-safe class 1 power at 1.34 µm is 1.9 times that allowable in the 1.4-1.6 µm range.

Keywords: $Nd:YVO_4$, V:YAG, Passive q-switch, LIDAR, 1.3 µm, eye-safe

1. INTRODUCTION

The 1.34-µm line of the semiconductor-pumped laser material $Nd:YVO_4$ is an efficient, high-gain laser transition at a wavelength with a particularly low eye hazard. This laser line can be effectively q-switched by the saturable absorber Vanadium:YAG, which has a fast recovery time[1], enabling repetition rates exceeding 1 MHz.

I report a 1.34-µm passively-q-switched laser with pulse duration 1.08 nsec FWHM, pulse repetition rate 24 kHz, and peak power 1.75 kW. The laser is diffraction-limited and polarized. In another configuration, optimized for repetition rate instead of peak power, the corresponding performance is 4.8 nsec, 1.82 MHz, and 68 W. Intermediate cases are also described. Pump power is at most 3.5 W, optical.

Compared to earlier work using these materials[2,3], the repetition rate is higher or the pulse length shorter, making this laser type more useful for LIDAR.

Compared to fiber-based lasers used in many eye-safe LIDAR systems, this type of laser is potentially smaller, less expensive and presents less of an eye hazard for a given power. A semiconductor-pumped, passively-q-switched laser has a near part-for-part correspondence with green pointer lasers sold for under $5 which are the size of a penlight. According to the 2014 ANSI standard[4], the eye-safe class 1 power at 1.34 µm is 1.9 times the allowable power in the 1.4-1.6 µm range.

I present theory and material properties useful for adjusting the performance of these lasers. I also describe trade-offs and limits related to pulse timing stability.

1.1 Laser Description

Figure 1 diagrams the laser. This type of laser has been termed a "microchip" laser[5] because the laser components are small and have only planar surfaces. The parts I have used are typically 5 mm x 5 mm x 1 mm, but in a product even smaller transverse dimensions are possible, keeping the cost of components low. The laser I have used has three components in the laser resonator – the $Nd:YVO_4$ laser gain element, which has the highly-reflecting resonator mirror on its first surface; the V:YAG saturable absorber which acts as a passive q-switch; and the output mirror. In a product, only two parts would be needed, as the output coating could be applied to the saturable absorber.

A semiconductor laser pumps the $Nd:YVO_4$. I have used an 808 nm laser with power up to 3.5 W. The more powerful pump lasers which are available at 885 nm could also be used. The laser of Figure 1 has an exact part-for-part correspondence with green pointer lasers which are small and inexpensive. Green pointer lasers have a nonlinear crystal – typically KTP – while this laser has a V:YAG saturable absorber, but the fabrication costs should be identical.

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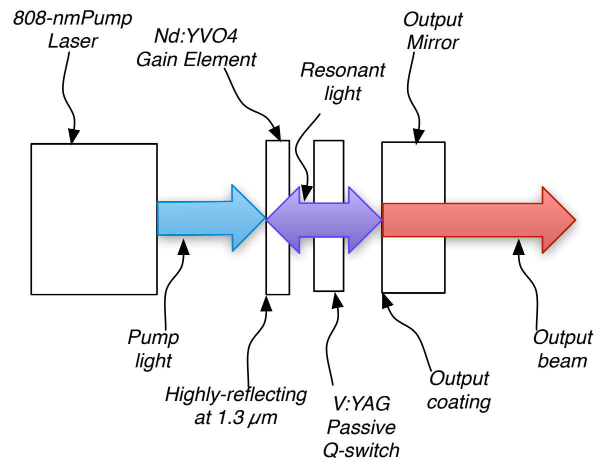

Figure 1. Schematic diagram of laser. The gain element is 1 mm thick, and the passive q-switch varied in thickness from 0.16 to 1.22 mm. The overall resonator was never more than 5 mm in length. The transverse dimensions of parts were about 5 mm x 5 mm, but smaller is possible, as the beams are typically 0.1 mm in diameter.

1.2 Positive features of this laser design for LIDAR use

Eye safety

The eye can tolerate the most light when that light is in the wavelength region between 1.2 and 1.4 µm. This is due to the fact that there is enough absorption by water in the bulk of the eye to keep light from reaching the retina, but not so much that power is concentrated in the first fraction of a millimeter. Absorbed power is distributed in a way that minimizes harm. Both the ANSI and IEC standards recognize this by setting the allowable Class 1 power, the power at which a laser is considered to be safe, at its highest in this region. In this wavelength range only, the two standards disagree, with the ANSI standard being stricter. Figure 2 shows the class 1 power as a function of wavelength for both standards. The ANSI standard allows 1.9 times more power at 1.34 µm as compared to 1.5 µm, and 18 times more as compared to 910 nm. Calculating the allowable power for a LIDAR system with a quickly-scanned beam is complicated and will generally lead to a significantly higher allowable power. In most cases the advantage of the 1.34 µm wavelength will still exist.

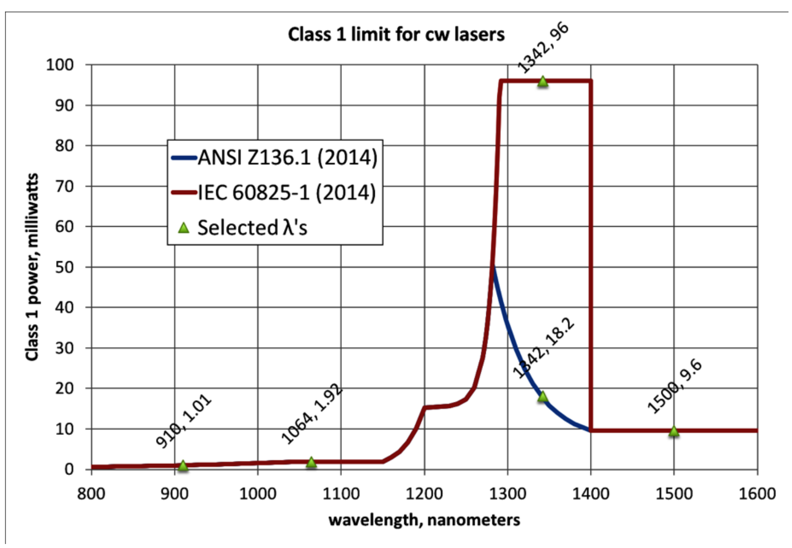

Figure 2. Class 1 "eye-safe" laser power as function of wavelength for a laser with a small, collimated beam. The wavelength range between 1.2 and 1.4 µm is the range of greatest allowable power, because water absorption is enough to protect the retina, while not so much that absorbed power is concentrated right at the surface. The two standards agree at all wavelengths except the range from 1280 nm to 1400 nm. In this range, the ANSI standard is stricter.

Nanosecond, kilowatt pulses without fast electronics

The nanosecond-range pulses from these lasers allow range resolution measured in centimeters. These short pulses are created by the dynamics of the laser. No high-speed, high-current drive electronics are required. As will be described, there is a trade-off between repetition rate and pulse duration, but at repetition rates up to 100 kHz it is possible to get peak power well above a kilowatt and rise time well below 2 nsec. Figure 3 shows a pulse recorded on a 1 GHz oscilloscope. This laser had a pulse repetition rate of 24 kHz.

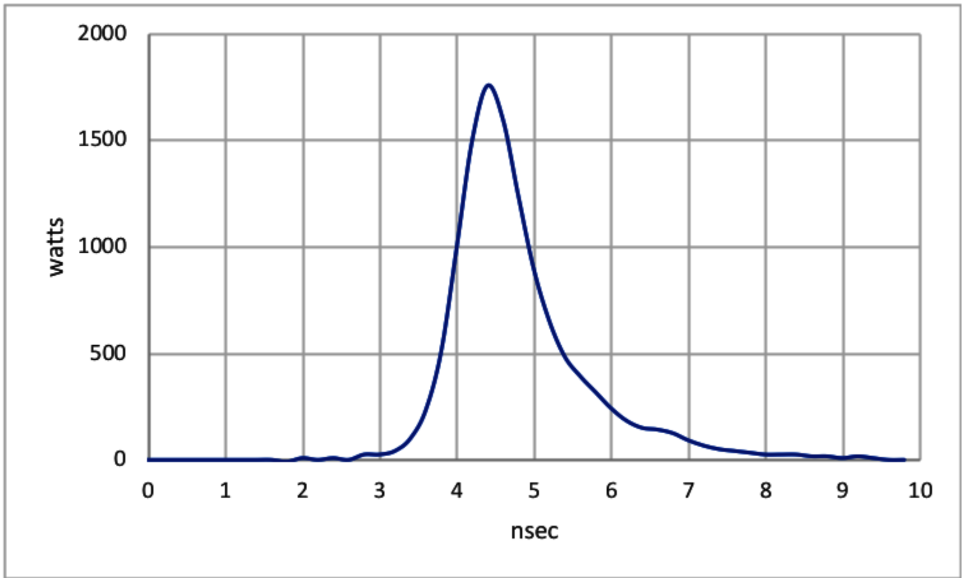

Figure 3. Oscilloscope trace of laser pulse. Pulse full-width at half-maximum is 1.08 nsec. The 10% to 90% rise time is 0.75 nsec. Peak power was 1.75 kW, and pulse energy was 2.5 µJoule. Pulse repetition rate was 24 kHz.

Diffraction-limited and polarized output

A diffraction-limited beam allows all the optics in the output beam line to be as small as theoretically possible. A small output lens will reduce system cost. A smaller beam is also easier to modulate and scan. Some modulators and scanners also prefer a polarized beam.

The output of a $Nd:YVO_4$ laser is naturally polarized, since laser gain is much stronger on one crystalline axis compared to the others. By fabricating the gain element with this crystalline axis oriented as desired, the laser polarization is determined.

Semiconductor-laser-pumped microchip lasers such as the one described here will have diffraction-limited output if the pumped volume within the $Nd:YVO_4$ gain element is smaller than the fundamental, or TEMoo, mode volume of the laser resonator. Establishing this condition requires tight focusing of the pump light and may require adjusting resonator length longer than would otherwise be desired.

All lasers described in this paper were pumped by an industry-standard fiber-coupled semiconductor laser, with its output beam shaped by a pair of lenses. Figure 4 is a photograph of the type of pump laser used. The output fiber has a 0.105 mm core. The N.A. of the output beam from the fiber was 0.12.

Figure 4. All lasers described in this paper were pumped by an 808 nm semiconductor laser with the package type shown. The output fiber has a 0.105 mm core and an output beam with N.A of 0.12. . For scale, the dimensions of the metal enclosure are 11.9 mm x 8.5 mm x 7.7 mm.

Precisely defined wavelength

Some LIDAR system are sensitive to background light, and a narrow-pass filter on the input may be needed. In this case, the wavelength of the filter and the laser must be matched. The physics of Nd:YVO_4 tightly constrains the wavelength to a range of 1342±0.5 nanometers.

Figure 5 shows atmospheric transmission from sun to ground over a range near 1342 nm, for a typical time of day at a mid-latitude location, for an atmosphere of standard humidity and temperature[6]. At 1342 nm, 47% of sunlight reaches the ground, somewhat reducing solar interference. The amount of air used for this data set is equivalent to a 12.8-kilometer path at sea level, so there will be no noticeable attenuation in a 1342 nm beam for paths on the order of a kilometer. The 1/e absorption depth at sea level for 1342 nm is 16 kilometers. It is interesting to note that just above 1342 nm, the atmosphere becomes opaque. There is a weaker laser line of Nd:YVO_4 at 1386 nm, where the atmospheric absorption depth is 1.1 km.

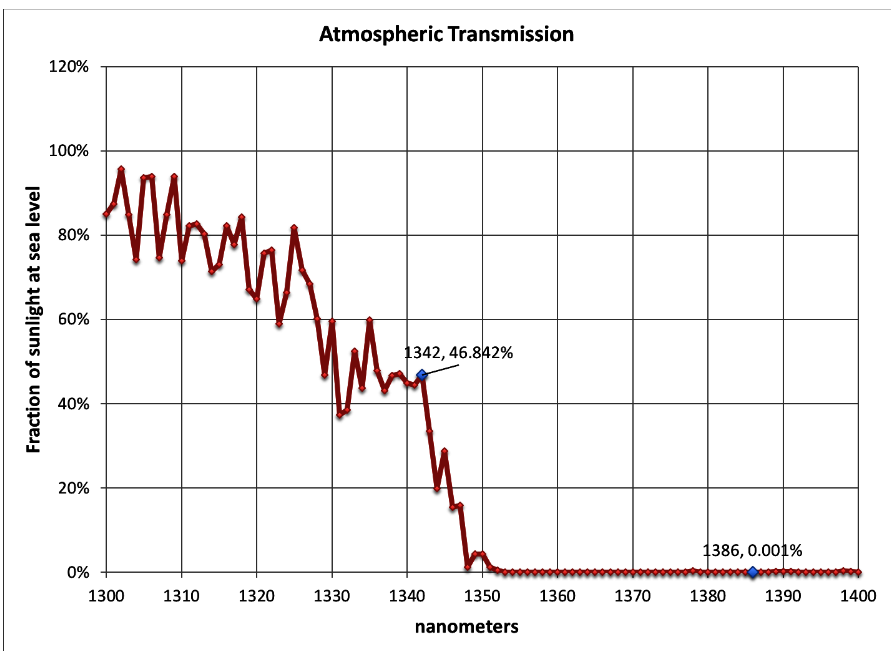

Figure 5. The transmission of a standard atmosphere for wavelengths near 1342 nm. At 1342 nm, there is attenuation equivalent to a 1/e absorption depth of 16 kilometers. This moderately reduces solar background, without significant signal attenuation for typical LIDAR systems.

1.3 Determinants of pulse timing in passive q-switching

Since there are no nanosecond-level control electronics required for this laser, there is no way to precisely control pulse timing. Even in an ideal system there will be pulse randomness of a few pulse lengths, due to the fact that each q-switched pulse builds up from quantum noise. In real systems the uncertainly in pulse timing can be much more. LIDAR systems based on passively q-switched lasers need to be designed with this in mind. The outgoing pulse must be detected and that signal fed to the timing circuitry which determines range.

Though jitter in the timing is unavoidable, there are techniques which can exactly control the number of pulses, ensuring that there is exactly one pulse in a given timing window. One approach takes advantage of the fact that when power from the semiconductor pump laser is increased, the pulse repetition frequency increases linearly, with the energy and length of each pulse remaining the same. A "phase-locked loop" can control the current to the semiconductor pump laser and hold pulse repetition frequency constant. Another technique is to pulse the current to the semiconductor laser, with the current pulse length held just long enough to ensure one outgoing laser pulse for each pulse of the semiconductor laser. With typical pulse repetition rates below 1 MHz, this does not require fast control of current. Figure 6 shows the result of using this second technique. The red trace is the current, which was pulsed from 1 ampere to 3.8 amperes with pulse length 27 µsec and pulse repetition frequency 11 kHz. This corresponds to a 30% duty cycle. The blue trace is the laser, which had a pulse length of 1.3 nsec and a peak power of 1.9 kW.

This laser had a pulse energy of 3.2 µJ. The reduced duty cycle improves laser performance by reducing the temperature of the $Nd:YVO_4$.

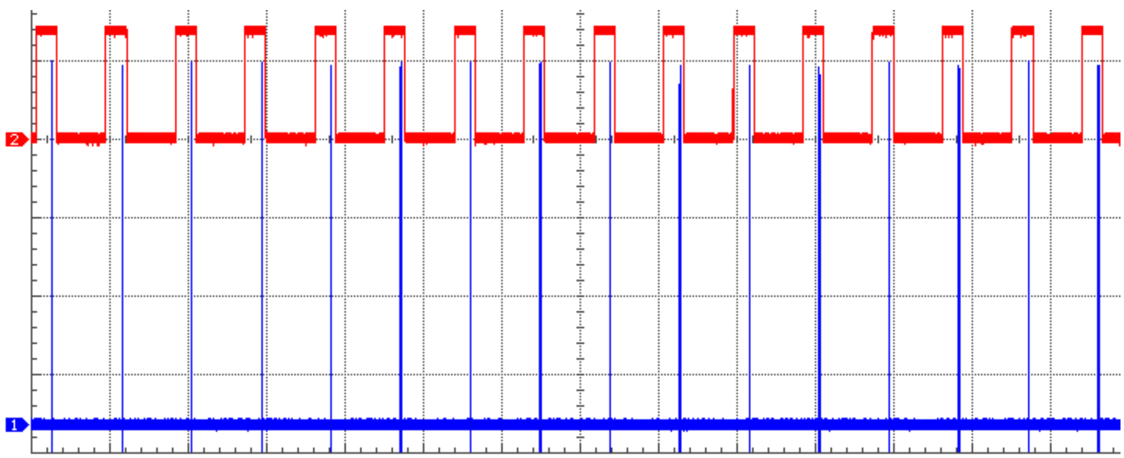

Figure 6. Demonstration of control of laser pulse repetition rate by means of pulsing the current to the semiconductor laser and setting the current pulse duration so that that there is exactly one laser pulse per current pulse. The horizontal scale is 100 µsec per division. The red trace is proportional to the current supplied to the semiconductor pump laser, which was modulated from 1 ampere to 3.8 amperes at a pulse rate of 11 kHz and a pulse duration of 27 µsec. The blue trace is the q-switched pulses. Pulses were stable in timing and power and had duration of 1.3 nsec and peak power of 1.9 kW. Some of the blue pulses may look stronger than others in the figure, but that is an artifact of the image.

Figure 6 shows the good stability in pulse energy and timing which is possible when there is significant time between pulses. The time between pulses in Figure 6 is 91 µsec, which is somewhat longer than the lifetime of energy stored in the laser material, called its "upper state lifetime," which is 61 µsec for the 2% doped material I am using[13]. When time between pulses is long compared to the upper state lifetime, the laser material "forgets" about the previous pulse and returns to the same starting point for each pulse. For high pulse repetition frequency, when there are many pulses within the upper state lifetime, there is a process which increases pulse-to-pulse variability. Adjacent pulses are in different axial modes of the laser, and because of the phenomenon known as spatial hole burning, each mode draws from distinct but overlapping sets of atoms. The first pulse will be in the mode which is closest to the wavelength of maximum gain. It will deplete its set of atoms, and the next pulse will be on a different mode, farther from the maximum gain. It will require more time to accumulate enough gain. This competitive process continues, with some degree of randomness and some degree of repetition. Figure 7 show a histogram of the time between pulses for a laser with an average pulse repetition frequency of 616 kHz, and thus an average time between pulses of 1.62 µsec. Over 171 pulses, the time between adjacent pulses varied from 1.25 µsec to 1.89 µsec, a variation of ±20%.

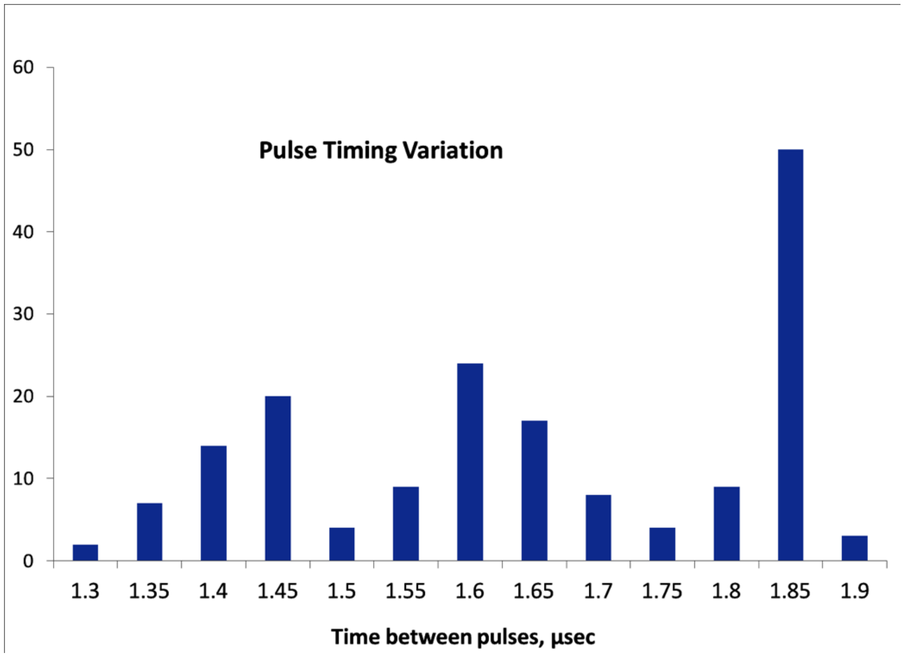

Figure 7. Histogram of time between adjacent pulses, for a laser with an average repetition rate of 616 kHz. Range corresponds to ±20%. The cause of the variation is the fact that different pulses are oscillating on different axial modes and see different gain.

There is also variation in pulse energy. Pulse duration has less variation. Figure 8 shows multi-pulse oscilloscope traces for two configurations, that of Figure 7, on the left, and that of Figure 6, on the right. The right-side case, with its lower repetition rate, shows better pulse-to-pulse consistency.

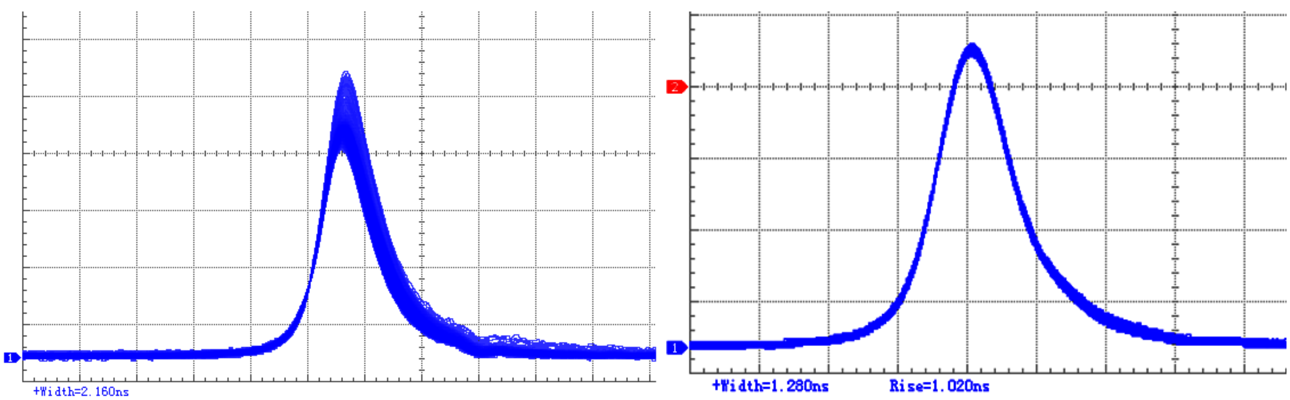

Figure 8. Multi-pulse oscilloscope traces for two configurations. The trace on the left side is for a laser with a pulse repetition rate of 616 kHz. Pulses vary in height. The right side is for a laser with a repetition rate of 11 kHz. Pulses are consistent. The horizontal scale is 2 nsec/div for the left side, and 1 nsec/div for the right. The oscilloscope was triggering on the pulses themselves so timing jitter is not apparent.

There are ways to reduce the pulse-to-pulse timing and energy variability of these lasers. They involve forcing the laser into a single mode or creating a balance between two modes of laser. This is an active research project for me. The approaches will probably increase the complexity and reduce the efficiency of these lasers. It is likely that the best way to deal with this variability is to design the overall LIDAR system to tolerate the variability. The power of modern signal processing may enable inexpensive approaches.

The variability may have one advantage. Where multiple LIDAR systems are in use, they may interfere with each other if they don't have a "code" or "signature" which distinguishes them. The variability of pulse timing can provide such a code or signature.

2. LASER MATERIALS AND PHYSICS

The goal of this section to explain what determines four important system properties: pulse duration; pulse repetition rate; pulse energy; and gain. The material parameters which determine these system parameters are described and tabulated.

2.1 Pulse duration

A passively-q-switched laser utilizes a material known as a saturable absorber. For the lasers described in this paper, the saturable absorber is Vanadium-doped yttrium aluminum garnet, or V:YAG. The host material YAG is the same crystal which, when doped with neodymium, is used for most high-power solid-state lasers.

The vanadium atoms of the saturable absorber, in their ground state, absorb light at 1.34 µm. When the pump laser of Figure 1 begins to pump the laser material, the laser does not lase instantaneously. Excited neodymium atoms build up in the laser material over many µsec. Only when the gain due to the excited atoms exceeds the losses of the laser resonator does lasing begin. The presence of the saturable absorber within the resonator results in a longer delay before lasing, and a greater amount of energy build up.

The unique feature of a saturable absorber is that once lasing is initiated, the saturable absorber quickly stops absorbing. The saturable absorber is like a dam that stops a river, but once the dam overflows, it is washed away and the water behind the dam creates a flood. It takes energy to open the saturable absorber – the vanadium atoms need to be pumped by the photons from the Nd:YVO_4 laser. The vanadium atoms transition to a higher energy state in which they ideally do not absorb at 1.34 µm. (They do continue to absorb, but much less, as will be discussed in the section on efficiency.)

Once the saturable absorber is out of the way, the light in the laser resonator builds up quickly. It uses up the stored energy, and the gain drops. The laser pulse does not stop when gain equals loss – in fact at that point the pulse has reached its peak, and the pulse is about half-way done. The falling side of the pulse extracts about as much energy as the rising side, and when the pulse is complete the laser is as far below the lasing point (the "threshold") as it was above threshold immediately after the opening of the saturable absorber.

The rate at which the pulse builds up is determined by only two parameters - the amount of absorption which disappeared when the saturable absorber opened, and the time it takes for light to make one round trip in the resonator. Less obviously, the pulse is close to symmetric in time, and the fall time is determined by the same two factors. Surprisingly, the output coupling and other losses do not affect pulse duration. This is strictly true only if the output coupling and other losses are large compared to the saturable loss, but it is close enough to true in general. The equation for the pulse duration is simple. The full-width at half-maximum pulse duration of a passively q-switched laser, τ_p, is given by[7,8]

$$\tau_p = 3.52\ T_R / q_0 \qquad (1)$$

where T_R is the round-trip time of light in the resonator, and q_0 is the amount by which the loss in the saturable absorber drops, again in a round-trip.

Here is an example case: The one-way resonator consists of 1 mm of Nd:YVO_4, 1 mm of air, and 1 mm of V:YAG. The index of refraction of Nd:YVO_4 is 2.15 and Nd:YAG is 1.81. The round-trip resonator optical distance is $2 \times 1\ mm \times (2.15+1.82+1) = 9.94\ mm$. The time for light to go that distance is $9.94\ mm / c = 0.033\ nsec = T_R$. If the saturable absorption of the V:YAG is 2% in a single pass, then the value of q_0, which is based on two passes, is $q_0 = 0.04$. Putting T_R *and* q_0 into (1) we get $\tau_p = 3.52\ T_R / q_0 = 0.825\ nsec$.

Equation (1) predicts results significantly shorter than actually achieved. It does give the proper scaling – if you want shorter pulses, use a shorter resonator, or more V:YAG. The value of q_0 is not simply the absorbance of the V:YAG, since some of the loss is not saturable. Šulc[9] measures the unsaturable loss to be 14% of the total loss.

2.2 Pulse repetition rate

As the Nd:YVO_4 gain element is pumped, the gain G builds up, asymptotically approaching a maximum gain level G_{max}. This maximum gain level G_{max} is linearly proportional to pump power. The difference between G_{max} and G is in the form of a decaying exponential, with an exponential time constant equal to the upper state lifetime τ_{Nd}, which is 61 µsec for the 2%-doped Nd:YVO_4 I am using. Figure 9 shows this equation for $G_{max} = 20\%$.

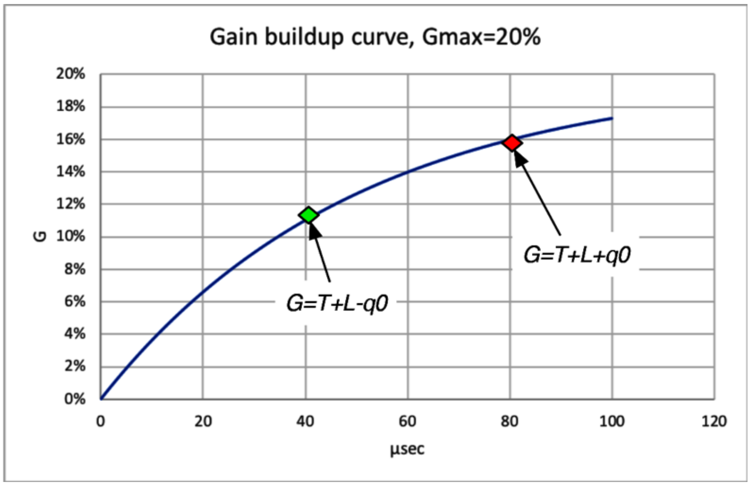

Figure 9. Gain builds up asymptotically to approach maximum gain G_{max} with the difference $G_{max} - G$ a decaying exponential with time constant $\tau_{Nd} = 61\ \mu sec$. In a passively q-switched laser, gain cycles between the two marked values of gain. The maximum gain achieved is shown by the red diamond and the minimum by the green diamond.

The red diamond indicates the maximum gain of the laser which occurs when lasing initiates, that is, when gain G is equal to output coupling T plus undesirable loss L plus saturable loss q_0. The green diamond indicates gain after the pulse is done. As described in the previous section, the gain drops to $T+L$, the resonator losses with the q-switch open, half-way through the pulse. The pulse is roughly symmetric and continues to extract energy and reduce gain until at the end of the pulse the gain G has dropped by $2q_0$.

It is straightforward to solve for the time T_{rr}, the time between the two end points. It is

$$T_{rr} = \frac{1}{rep.rate} = \tau_{Nd} \ln\left(\frac{G_{max}-T-L+q_0}{G_{max}-T-L-q_0}\right) \tag{2}$$

There is a solution only if $G_{max} > T + L + q_0$; otherwise the laser never reaches threshold.

2.3 Pulse energy

The conversion efficiency is the ratio of time-averaged optical power produced by the laser to the power delivered by the semiconductor laser to the gain element. One factor in the efficiency is the fraction of light absorbed by the gain element. This is high, typically over 90%, since Nd:YVO_4 has high absorption at the pump wavelength. Another factor is the ideal conversion efficiency of 808 nm light to 1342 nm light. The Stokes efficiency, which would occur if photons were converted 1 for 1, is 60%. This is reduced by the phenomenon of excited state absorption[10]. There are also miscellaneous losses. In my experience a conversion near 30% is typical when all these losses are combined. That is a typical slope efficiency of a simple cw laser with an output coupler much larger than any other resonator losses. The starting point for the analysis of q-switched output energy is the value I call P_{avail}, the available power, which is 30% of the optical pump power.

The maximum theoretical pulse energy, E_{avail}, which would result if all of the stored energy were extracted in a single pulse, is given by $E_{avail} = \tau_{Nd} P_{avail}$. A fractional change in gain G will result from an equivalent fractional change in stored E. When a pulse occurs, the reduction in gain ΔG divided by the maximum gain G_{max} is equal to the extraction of energy E_{ext} divided by the maximum extractable energy E_{avail}. Recalling that the change of gain during a pulse is $2q_0$, we get

$$\Delta G/G_{max} = 2q_0/G_{max} = E_{ext}/E_{avail} \tag{3}$$

from which it follows that the extracted energy $E_{ext} = 2\ P_{avail}\ \tau_{Nd}\ q_0\ /\ G_{max}$. The actual output energy is reduced by the ratio of output coupling to total losses, which is $T/(T+L)$ so output pulse energy E is given by

$$E = \frac{T}{(T+L)} \frac{2\,P_{avail}\,\tau_{Nd}\,q_0}{G_{max}} \tag{4}$$

The peak q-switched power is roughly E/τ_P. The time-averaged q-switched power is $E \bullet (repetition\ rate) = E/T_{rr}$.

These equations I have presented will not lead to exact calculations or precise modelling because important input values such as G_{max} or q_0 are not known well. They are a useful guide to what should be changed to achieve a desired result.

2.4 Gain

The gain G_{max} can be calculated using the equation

$$G_{max} = E_{avail}\, \sigma / (A\, h\nu) \quad (5)$$

where σ is the gain cross-section of Nd:YVO$_4$ at 1342 nm, given in Table 1, $h\nu$ is the energy of a photon of 1.342-µm light, 1.48×10^{-13} µJ, and A is the cross-sectional area of the pump beam, under the simplifying assumption that the cross-sectional area of the lasing mode is the same and that for both beams light is uniform over that area. This is an oversimplification, but the goal of this section is to understand general trends rather than to enable exact calculation. Over the small range of pump beams used, the effects of thermal lensing and gain guiding did cause the laser mode to track the pump beam, and Equation (5) does correctly predict scaling.

This important parameter A can be controlled using lens pairs configured as a telescope. I have used two telescopes, one with magnification of 1 and the other with magnification of 0.6. The input beam to the telescope has a diameter of 0.105 mm, so with the 1:1 telescope the diameter of the beam in the pumped volume is unchanged, and the area $A=8.7x10^{-3}\ mm^2$. The telescope with the magnification of 0.6 reduces this area to $A=3.1x10^{-3}\ mm^2$.

I am pumping with a 3 W semiconductor laser, so $E_{avail} = 3\ W \bullet 50\ \mu sec \bullet 30\% = 45\ \mu J$. Using (5) the two values of G_{max} are calculated to be 0.91 and 2.55. These numbers are higher than reality, probably due to the fact that area A was estimated ignoring pump beam divergence within the pumped volume.

2.5 Active Laser Materials

The properties of the materials Nd:YVO$_4$ and V:YAG have been studied. The earliest work was by Malyarevich[1] with further measurements Šulz[9]. Historically the most common type of passively q-switched laser uses Nd:YAG as the gain material and Cr:YAG as the saturable absorber. That material combination lases at the wavelength of 1.064 µm. I will provide material properties on both laser types so that those familiar with the 1064 nm system can quickly see how it compares to the 1342 nm system.

There are five laser material properties of interest. They are:

- the gain cross-section of the gain material, called σ above;
- the pump absorption cross-section of the laser material σ_{pump};
- the upper state lifetime of the laser material, called τ_{Nd} above;
- the absorption cross-section of the saturable absorber σ_{sat};
- the upper state lifetime of the saturable absorber τ_{sat}.

Those values are tabulated in Table 1.

Table 1: Properties of laser materials. The reference for each value is in the cell next to the value.

Property	Nd:YVO$_4$ V:YAG		Nd:YAG Cr:YAG	
Wavelength of operation	1342 nm		1064 nm	
laser gain cross-section σ	2.6×10^{-17} mm^2	Ref. [11]	2.8×10^{-17} mm^2	Ref [12] p. 55
laser pump absorption σ_{pump}	2.7×10^{-17} mm^2	Ref [12] p. 71	0.41×10^{-17} mm^2	Ref [12] p. 71
laser upper state lifetime τ_{Nd}	61 µsec (2% doped)	Ref [13]	230 µsec	Ref [12] p. 55
saturable absorber σ_{sat}	7×10^{-16} mm^2	Refs [1,9]	7×10^{-16} mm^2	Ref [12] p. 525
saturable absorber lifetime τ_{sat}	0.022 µsec	Ref [1]	4.1 µsec	Ref [12] p. 525

It is notable that the cross-sections σ and σ_{sat} are almost identical for the two systems. The 1342 nm system has an advantage if high pulse repetition rates are required. Passive q-switching becomes inefficient and unstable if the repetition rate is faster than the inverse of the saturable absorber lifetime τ_{sat}, limiting the 1064 nm system to about 250 kHz. An advantage of the 1064 nm system is greater pulse energy at low repetition rates due to the longer upper state lifetime of the gain material τ_{Nd}.

A significant advantage of Nd:YVO_4 in general is the high cross-section for pump absorption, σ_{pump}. The pump bands are also wider for Nd:YVO_4, making pump specification and temperature control easier.

The ratio of σ_{sat}/σ_{Nd} is 25 for both systems. A value greater than 10 is considered necessary for stable passive q-switching. The reason that there are no Nd:YVO_4 lasers at 1064 nm passively q-switched by Cr:YAG is the fact that σ_{Nd} at that wavelength is too high, and the σ_{sat}/σ_{Nd} ratio is not in the stable range.

3. EXPERIMENTAL RESULTS

Vanadium:YAG samples in the form of 5 mm x 5 mm squares were obtained at four thicknesses. These were provided by Krytur of Turnov, Czech Republic, and were anti-reflection coated on two parallel surfaces. The three equivalent [100] axes of the YAG were oriented normal to the faces and the edges. Table 2 provides information on the four V:YAG thicknesses.

Table 2: V:YAG samples

Thickness	Transmission at 1.34 µm, single-pass
0.16 mm	97.5%
0.325 mm	95%
0.67 mm	90%
1.22 mm	79%

The Nd:YVO_4 used for these experiments was in the form of 6 mm x 5 mm rectangle, 1 mm thick, 2% doped. One surface was coated for high reflectivity at 1.34 µm and high transmission at 808 nm, the other for low reflectivity at 1.34 µm. The high-gain "c" axis was aligned with the 6 mm dimension.

The V:YAG [100] axis should be aligned with the Nd:YVO_4 "c" axis for best performance[9].

Two output couplers were used, 4% and 14%.

As described earlier, the pump was based on an 808 nm fiber-coupled semiconductor laser. The fiber has a 0.105 mm core diameter, and the divergence N.A was measured to be 0.12. Two telescopes, both based on pairs of molded aspheres with short focal lengths, re-imaged the fiber face on to the Nd:YVO_4. One telescope had magnification M=1, the other had M=0.6. The light from the fiber was unpolarized.

All measurements presented below were made with a current to the semiconductor of 4 amperes or less. At 4 amperes, the optical output from the fiber was 3.5 W.

Figure 10 shows cw results, using the 4% output coupler and the M=1 pump telescope. The slope efficiency was 30% and the threshold was 0.39 W.

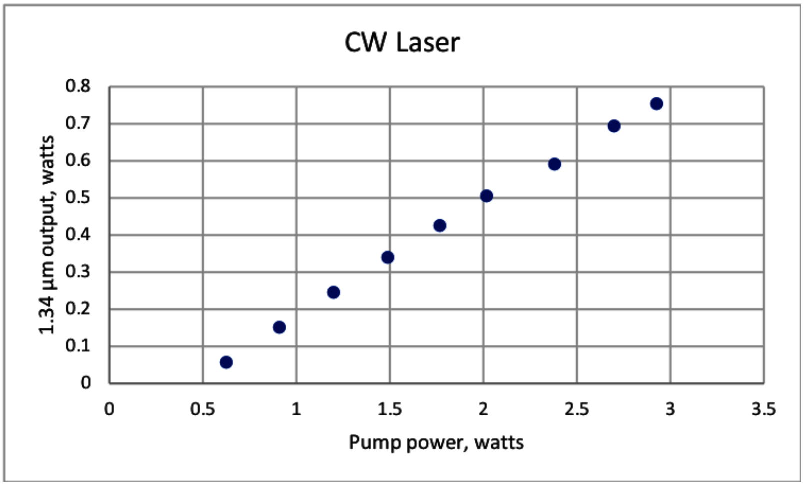

Figure 10. Continuous-wave results. Slope efficiency is 30%. Pump power is incident power.

The best pulse energy was achieved with the M=1 pump, the 14% output coupler, and the 0.67 mm thick V:YAG. Figure 11 shows average power and repetition rate plotted as a function of pump power. The slope efficiency was 16% and the threshold was 0.67 W. In Figure 11 the blue data is average power, and the orange is repetition rate. They are highly correlated, indicating that pulse energy is nearly constant. At 2.9 W pump the average power was 0.35 W and the repetition rate was 92 kHz, giving a pulse energy of 3.8 µJ. Pulse duration FWHM was 1.6 nsec.

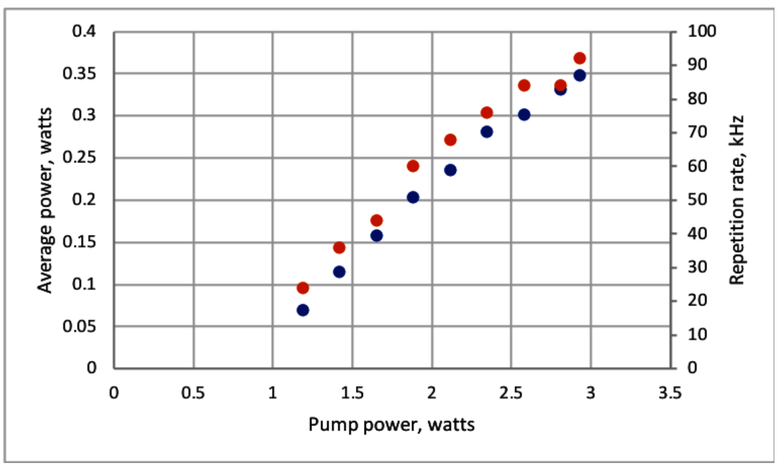

Figure 11. Q-switched results with 0.67 mm V:YAG in resonator. Blue points are average power and orange are repetition rate. Pulse energy was 3.8 µJ at the maximum pump and varied little over the full range of pumping. Pulse duration was 1.6 nsec.

The data of Figure 12 was taken with two changes – the output coupler was changed to 4% and the pump beam was smaller, as the M=0.6 telescope was used. The slope efficiency is 12% and the threshold is 0.38 W. The correlation between repetition rate and power is excellent. The pulse energy at all repetition rates was 0.8 µJ. The pulse duration was 1.6 nsec, as shown in Figure 13.

The effect of the smaller pump beam and lower output coupling is clear. The repetition rate went up by a factor of 4.5, and the pulse energy came down by a factor of 4.7. The increased repetition rate can be understood qualitatively by looking at Equation (2). Reducing output coupling T and increasing gain G_{max} both push repetition rate up. They also push threshold down. Equation (4) shows how increased G_{max} and reduced T work to reduce pulse energy. The lower efficiency is probably due to the fact that T is too low . The primary source of loss L is probably the V:YAG itself. As well as having saturable loss, it has unsaturable loss due to exited state absorption. This has been measured at 16% of the saturable loss[9].

As expected from Equation 1, pulse duration did not change, since the resonator and the V:YAG used were the same.

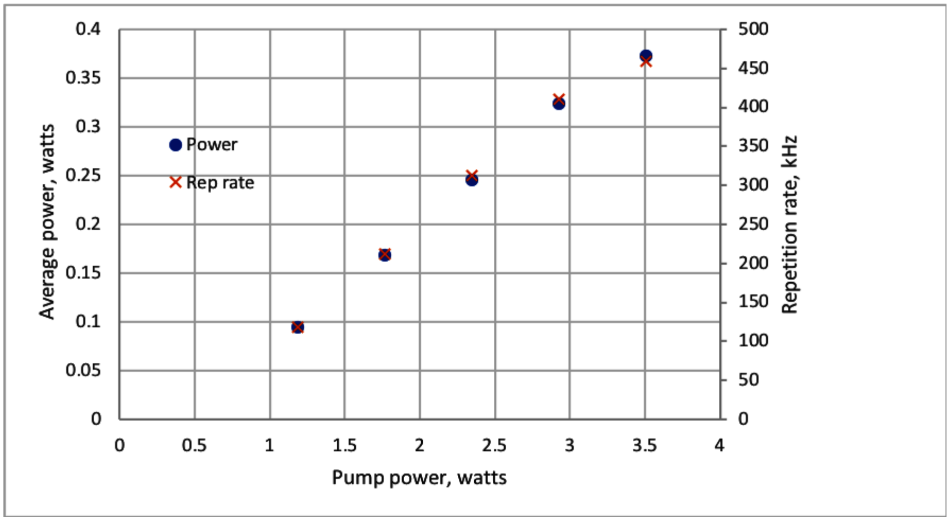

Figure 12. Same V:YAG as Figure 11, but with more tightly focused pump beam and lower output coupler. Pulse energy was 0.8 µJ at all pump powers. Pulse duration was 1.6 nsec.

Figure 3 shows an oscilloscope trace of pulses from the laser of Figure 12. The pulse energy was bi-modal, with the big pulses 1.5 times more powerful than the small pulses. Time between pulses varied similarly. The pulse duration did not vary as much from pulse to pulse.

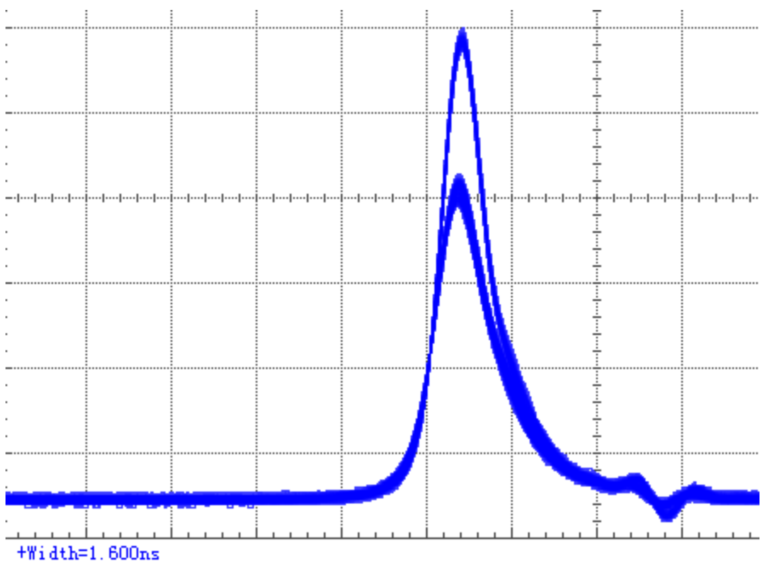

Figure 13. Multi-pulse oscilloscope trace from laser of Figure 12, showing 1.6 nsec FWHM and bi-modal pulse energy distribution.

In order to maximize repetition rate, I used the thinnest (0.16 mm) piece of V:YAG with the tightly-focused pump and the 4% output coupler. Figure 14 shows the results. At repetition rate of 1.82 MHz was reached at pump power 3.5 W. Pulse energy was 0.4 µJ at all repetition rates. Pulse duration was 4.8 nsec at the highest repetition rate, and somewhat longer at lower repetition rates. Slope efficiency improved to 26% due to the lower level of unsaturable loss in the much thinner V:YAG.

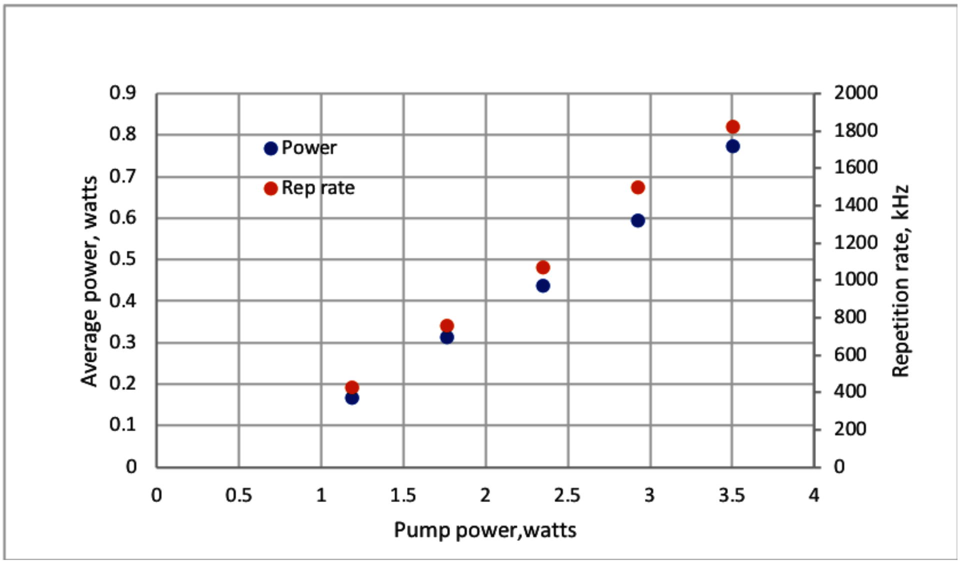

Figure 14. Repetition rate of 1.82 MHz, pulse energy of 0.43 µJ, and pulse duration of 4.8 nsec were achieved with the 0.16 mm V:YAG, the tighter pump focusing, and the 4% output coupler.

The shortest pulses, but not the highest energy, were produced with the thickest piece of V:YAG. The pulse shown in Figure 3 was produced using the 1.22-mm V:YAG, the larger pump beam, and the 4% output coupler. Pumping was at 2.9 W, pulse energy was 2.5 µJ, and pulse FWHM was 1.08 nsec. The results shown in Figures 6 and 8b, produced with a 3.3-W pump at 30% duty cycle, were achieved in the same laser configuration. The reduced duty-cycle pumping raised the pulse energy to 3.2 µJ and raised the pulse duration to 1.3 nsec. The likely cause of reduced pulse energy relative to the laser of Figure 11 is the large amount of unsaturable loss associated with the thickest V:YAG. Using the higher output coupler might improve efficiency, but not every worthwhile experiment gets done before the paper deadline.

Table 3: Summary of all of the results presented above, plus two more configurations.

Data in Figure	V:YAG	Pump beam diameter	Output coupling	Pump power	Repetition rate	Pulse energy	Pulse duration FWHM	Energy/ duration*
14	0.16 mm	0.063 mm	4%	3.5 W	1820 kHz	0.43 µJ	4.8 nsec	89 W
	0.16 mm	0.105 mm	4%	3.0 W	680 kHz	0.92 µJ	6.4 nsec	144 W
7, 8a	0.32 mm	0.063 mm	4%	3.0 W	616 kHz	0.76 µJ	2.2 nsec	344 W
	0.32 mm	0.105 mm	4%	2.9 W	295 kHz	1.38 µJ	3.6 nsec	383 W
12, 13	0.67 mm	0.063 mm	4%	3.5 W	460 kHz	0.8 µJ	1.6 nsec	500 W
11	0.67 mm	0.105 mm	14%	2.9 W	92 kHz	3.8 µJ	1.6 nsec	2400 W
6, 8b	1.22 mm	0.105 mm	4%	3.3 W, 30% duty	11 kHz	3.2 µJ	1.3 nsec	2500 W
3	1.22 mm	0.105 mm	4%	2.9 W	24 kHz	2.5 µJ	1.08 nsec	2300 W

*This is not the same as peak power but it is a useful and easily-calculated figure of merit. For the case in the last row, peak power was 1750 W, 76% of the tabulated value. This ratio should be typical.

An important practical consideration in any system is the tolerance to temperature change. The pump bands of solid-state lasers have fairly narrow absorption peaks, and semiconductor lasers tune with temperature. Of all the neodymium-doped crystalline solid-state laser materials, $NdYVO_4$ has the best ability to absorb pump light over a wide range. Figure 15 shows the temperature sensitivity of a laser configured to have a pulse repetition frequency of 114 kHz and an average power of 0.15 watts. The temperature of the semiconductor pump was tuned from 8°C to 35°C, while the current to the semiconductor laser was adjusted to keep repetition rate and average power constant. In the optimal temperature range of 25-30°C the required current was 2.7 amperes, but by adjusting current up to 4 amperes the entire 8-35°C range was usable.

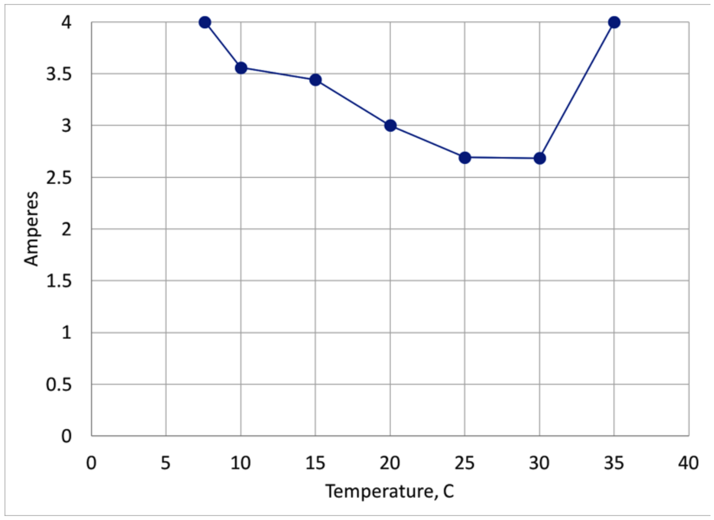

Figure 15. The repetition rate and average power of a laser were held constant over a range of temperature of the semiconductor laser pump by adjusting the current to the laser. The required current is shown for each temperature. With current compensation, a temperature range of 8-35°C was demonstrated.

4. CONCLUSIONS

Semiconductor-laser-pumped solid-state lasers based on the gain material Nd:YVO_4 and passively q-switched by the saturable absorber material V:YAG provide nanosecond pulses at the wavelength of 1.34 µm that could be valuable in LIDAR systems. Inexpensive lasers of similar design are widely used as green pointer lasers, demonstrating the potential low cost and simplicity of this design approach. The 1.34 µm wavelength is in a range of maximum eye-safety. The short pulses are achieved with simple electronics – no high-current, high-speed pulse forming is required, since the dynamics of the laser itself determine the pulse width. These lasers provide polarized, diffraction-limited beams which simplify and shrink the size of required output and beam-forming optics. Industry-standard semiconductor pumps can be used at the wavelength of either 808 nm or 885 nm.

These lasers are similar to "microchip" passively q-switched lasers based on the gain material Nd:YAG and the saturable absorber Cr:YAG. Advantages over that system are the ability to reach MHz pulse repetition rates, and the broader and stronger pump absorption of Nd:YVO_4, which relaxes tolerances on the semiconductor pump laser.

Pulse repetition rates up to 1.82 MHz were demonstrated. Best peak power was 1.75 kW in a pulse with 0.75 nsec 10%-to-90% rise time and 1.08 nsec full-width at half-maximum. There is a trade-off between repetition rate and pulse duration; at 1.82 MHz the peak power was 68 W and the pulse duration was 4.8 nsec. The shortest pulses were achieved at a repetition rate of 24 kHz.

At a repetition rate of 11 kHz pulse timing jitter was on the order of 1%. At higher repetition rates jitter of ±20% results from mode competition in the laser. Though jitter will still exist, it is possible to ensure exactly one pulse per pulse window by controlling the current to the semiconductor laser.

The key parameters that were adjusted to get the reported range of performance are the thickness of the V:YAG and the size of the pumped region in the Nd:YVO_4. By adjusting these parameters, lasers filling the range between the two extreme cases can be readily produced.

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