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Thomas J. Kane, John L. Nightingale, "Eye-safe passively-q-switched lasers at 1.3 µm with >1 W average power and nsec pulses," Proc. SPIE 12515, Laser Technology for Defense and Security XVIII, 1251509 (15 June 2023); doi: 10.1117/12.2663200

SPIE.

Event: SPIE Defense + Commercial Sensing, 2023, Orlando, Florida, United States

Eye-safe passively-q-switched lasers at 1.3 µm with >1 W average power and nsec pulses

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ABSTRACT

Diode-pumped, passively-q-switched neodymium lasers at wavelengths near 1.3 µm based on the saturable absorber Vanadium:YAG have favorable properties as sources for longer-range, >300 m, 3D-imaging systems which are difficult to implement with semiconductor lasers. This wavelength enables eye safety at exposures above what is permitted at 1.5 µm. The lasers are simple, comprising two millimeter-scale crystals with all plano surfaces. We report a Nd:YVO_4 laser with a pulse repetition rate of approximately 500 kHz and a Nd:YAG laser with a pulse energy of 40 µJ, both with pulse durations below 2 nsec.

Keywords: Nd:YVO_4, Nd:YAG, Yb:Er:YAB, V:YAG, Passive q-switch, LIDAR, 1.3 µm, 1.5 µm, eye-safe

1. INTRODUCTION

Semiconductor-pumped, passively-q-switched lasers operating at wavelengths longer than 1.2 µm are attractive laser sources for LIDAR, particularly for mid- or long-range applications where direct semiconductor laser sources operating near 900 nm are insufficiently bright or pose an eye safety hazard. These lasers can have a simple design with only a gain element and saturable absorber present in the passively-q-switched laser cavity. A passively-q-switched laser has a near part-for-part correspondence with an inexpensive green laser pointer.

This paper extends earlier work reported by one of the authors[1] and reports new results using V:YAG as the saturable absorber and either Nd:YVO_4 or Nd:YAG as the gain element. We have designed and characterized lasers optimized for short pulse generation at high repetition rate or high pulse energy. These lasers produce light at eye-safe wavelengths near 1.3 µm. We built and characterized many different laser configurations. Depending on the laser configuration, we observed pulse energies ranging from 2.5 to 40 µJ, pulse repetition rates ranging from 1 kHz to over 500 kHz, with all pulses having a pulse width of 5 nsec or shorter. The maximum average power was 1.45 W.

Passively-q-switched lasers with wavelengths in the range 1.5-1.6 µm can be produced using crystals co-doped with ytterbium and erbium as the gain element and Co:$MgAl_2O_4$ as the saturable absorber. The erbium provides the gain. The most efficient of these erbium lasers make use of rare-earth borates as the host crystal[2]. The most readily available of these ytterbium-erbium doped rare earth borates is Yb:Er:$YAl_3(BO_3)_4$, often denoted as Yb:Er:YAB.

In this paper we tabulate and compare material properties and our experimental results for the two neodymium-doped laser materials with corresponding data for Er-based lasers. The most significant difference in properties between the neodymium and the erbium laser materials is the cross-section for stimulated emission, which is lower for the erbium-doped materials. This difference creates advantages for the Nd-based lasers, both in their q-switched efficiency and in their ability to produce short pulses at high repetition rates. Our experimental results confirm the advantage of the Nd-based lasers over Er-based lasers for eye-safe ranging at high repetition rate.

1.1 Attributes of passively-q-switched lasers

Various attributes of passively q-switched diode-pumped lasers are particularly attractive for LIDAR. A first attribute is eye safety. The allowable Class 1 power level rises strongly as wavelength lengthens beyond 1.2 µm, reaching a maximum in a range including 1.3 µm and then declining but remining high for wavelengths longer than 1.4 µm. The ANSI standard allows 1.9 times more power at 1.34 µm as compared to 1.5 µm, and 18 times more power as compared to 910 nm. A second attribute of these lasers is that they produce nanosecond duration pulses without any high-speed electronics. The gain element in the passively-q-switched resonator stores pump energy, which is then suddenly released in a q-switched

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Laser Technology for Defense and Security XVIII, edited by Mark Dubinskii, Rita D. Peterson,
Proc. of SPIE Vol. 12515, 1251509 · © 2023 SPIE · 0277-786X · doi: 10.1117/12.2663200

pulse. Peak powers can exceed 1 kW, a power level which cannot be achieved in a semiconductor laser having a single emitting aperture. A third attribute is that these lasers can have a diffraction limited output beam. This enables projecting a collimated beam for long distances using small aperture optics. A fourth attribute is that these lasers can have a polarized output, which can simplify the overall optical system. A fifth attribute is that the output wavelength of these lasers is in many cases precisely defined by the atomic transition in the gain element. Thus, in a LIDAR system, optical filters having a transmission window of 1 nm or less may be used to filter out background light. A sixth attribute is the laser's small size. We anticipate that manufactured passively-q-switched lasers can be made having a volume of around one cubic centimeter. While larger than a simple semiconductor laser, it is much smaller than fiber amplified systems operating near 1500 nm.

A possible disadvantage of a passively q-switched laser is that the timing of an emitted pulse is not accurately known prior to pulse emission. 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.

2. MATERIAL COMPARISONS

Table 1 lists important parameters for the two most widely used neodymium-doped laser materials and for a corresponding erbium-doped rare-earth borate gain material. Row one of Table 1 lists representative standard doping levels. The properties in subsequent rows of Table 1 are listed for these doping levels and may vary if different doping levels are used. For example, $Nd:YVO_4$ doping levels ranging from 0.1% to 3% are available, and absorption depth varies inversely with doping level.

Table 1. Comparison of different laser gain materials.

#	**Material**	**$Nd:YVO_4$**	**Nd:YAG**	**Yb,Er:YAB**
1	Doping	1% Nd	1% Nd	11% Yb,1.5% Er
2	Eye-safe lasing wavelengths	1342 nm	1319 nm 1338 nm	1522 nm *Ref [3]* 1531 nm *Ref [2]* 1555 nm *Ref [2]*
3	Class I eye-safe power, US (ANSI)	18 mW	18 mW	9.6 mW
4	Class I eye-safe power, Europe (IEC)	96 mW	96 mW	9.6 mW
5	Gain cross section (10^{-20} cm^2)	26 *Ref [4]*	10 *Ref [5]*	2.6 *Ref [2]*
6	Excited state lifetime	100 µsec *Ref [5]*	240 µsec *Ref [5]*	325 µsec *Ref [2]*
7	Cross-section-lifetime product	2600	2400	850
8	Pump wavelength and tolerance	809±5 nm 879±1.5 nm	806.5±2 nm 869±1 nm 885±1.5 nm	976±8 nm
9	Saturable absorber material	V:YAG		$Co:MgAl_2O_4$
10	Saturable absorber cross-section (10^{-20} cm^2)	700 *Ref [6]*		35 *Ref [7]*
11	Saturable absorber excited state lifetime	22 nsec *Refs [6, 8]*		350 nsec *Ref [7]*
12	Optical-optical slope efficiency, cw operation	35%	35%	35% *Ref [2]*
13	Pump and output polarized	Yes	No	Yes
14	Pump 1/e absorption depth, mm	0.3 at 808 nm 0.6 at 879 nm	7 at 885 nm 4 at 869 nm 1.6 at 808.5 nm 4 at 806.5 nm	0.6
15	Thermal conductivity, W/(m•K)	5 *Ref [5]*	11 *Ref [5]*	7.7 a-axis 6 c-axis *Ref [9]*

The second row in Table 1 tabulates the eye-safe wavelengths produced by each material. For Nd:YAG and Yb:Er:YAB more than one wavelength are possible. With appropriate choice of optical coating reflectivity, a particular wavelength can be selected. An advantage of $Nd:YVO_4$ is that no such selective coating is required to achieve single-wavelength operation. A single wavelength, determined by laser physics, may be advantageous to a LIDAR system designer in that a narrow bandpass filter can be used on the return beam with confidence that the laser will remain in the chosen passband.

Rows three and four in Table 1 tabulate the Class-I eye-safe power for the lasing wavelength. At this power level a cw laser with a small, collimated beam can be used in a public space. For a practical LIDAR system, with a quickly scanned, pulsed laser, the limits will be quite different, and in general higher. However, the allowable Class I power is a useful baseline for comparing safety. Figure 1 is a plot of Class-I eye-safe laser power as a function of wavelength.

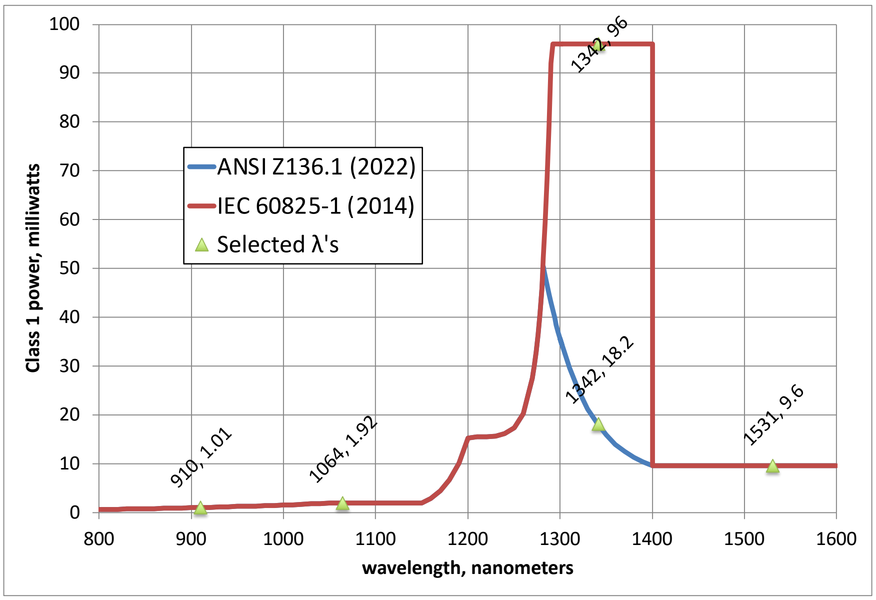

Figure 1. Class 1 power limit for cw lasers with a small, collimated beam as a function of wavelength.

Both the erbium- and neodymium-based lasers are safe at far greater levels of exposure than are lasers operating at 0.91 µm, a common wavelength for LIDAR systems, where the Class I limit is 1 mW. At 1.5 µm the safe exposure limit is approximately an order of magnitude higher than at 0.91 µm.

There are two eye safety standards, the United States (ANSI[10]) and the European (IEC[11]) standard. The European standard allows an additional order of magnitude increase in the exposure limit for neodymium eye-safe lasers above the erbium wavelength. The US standard is more restrictive, but still allows significant additional exposure.

The rationale behind this window of maximized eye safety near 1.3 µm is the tradeoff between damage to the retina and damage to an eye's surface layer. At visible and near-IR wavelengths the retina is the primary concern. As the wavelength moves farther into the infrared, the increasing absorption of water and the decreasing absorption of retinal tissue provide protection to the retina. At wavelengths of strong water absorption, such as 1.4 µm and longer, the concern becomes damage to the eye's surface. When the light is absorbed in the first fraction of a millimeter, as it is for wavelengths longer than 1.4 µm, surface heating become the limiting damage mechanism.

The wavelengths near 1.3 µm provide an optimum safe zone between retina damage and surface damage. Light is absorbed in the first few millimeters of eye tissue, so the eye tissue temperature rise is reduced compared to the case of absorption on the surface, since the absorption is spread out over a larger volume of eye tissue.

Row five of Table 1 provides the "cross-section for stimulated emission" of the neodymium or erbium ions in the laser materials. The value for $Nd:YVO_4$ is notably larger than that of the other two materials, while the erbium cross-section is smaller than the cross-section for both neodymium materials. The cross-section is critical, since it determines how much gain a laser will have for a specific amount of stored energy. The greater gain of $Nd:YVO_4$ enables lasers which simultaneously provide high repetition rate and short pulse duration. At the reduced cross-sections of Nd:YAG and Yb:Er:YAB, short pulses remain possible, though only at lower pulse repetition rate. An advantage of the lower repetition rate is a correspondingly larger pulse energy.

Row six of Table 1 shows the excited state lifetime of the energy level which provides laser gain. For lasers operating at low repetition rates (defined as less than the reciprocal of the excited state lifetime) this parameter is important, since it is the time over which pump power can be integrated to determine total energy storage.

For higher repetition rates, the product of the cross-section and the energy storage time is important. This product is tabulated in row seven of Table 1. When this product is large, it takes less pump power for the laser to reach threshold enabling efficient operation well above threshold.

Row eight of Table 1 shows the wavelengths at which the materials can be optically pumped. The wide tolerance and long wavelength of the erbium doped gain element is an advantage. More power is available from semiconductor lasers at wavelengths near 976 nm compared to wavelengths of 808 nm, with intermediate wavelengths generally having increasing power with increasing wavelength in the interval between these two wavelengths. There are pump wavelength bands for Nd lasers longer than the typically used 808 nm wavelength, but the pump absorption is narrow, so pump lasers stabilized by gratings are likely to be needed.

Row nine of Table 1 lists the saturable absorber materials used as passive q-switches for the tabulated laser materials. An ideal q-switch material will have three properties. First, it will have a cross-section for saturable absorption which is at least an order of magnitude larger than the laser gain cross section of row five. Second, it will have an excited-state lifetime which is longer than any desired laser pulse width. This prevents the saturable absorber reverting to a high absorption state while the laser pulse is still being generated. Both saturable absorber materials more than adequately meet these two criteria at their wavelength of operation, as shown in rows ten and eleven. A third desired characteristic is low unsaturable absorption, that is low “ordinary” loss. Unsaturable loss results in reduced efficiency. In our opinion, neither q-switch material has been well-characterized in this last respect, and as a result, the efficiency of these lasers is below what is calculated from models.

Row twelve of Table 1 shows that the Er- and Nd-based lasers have remarkably similar efficiencies in continuous wave operation. Differences in efficiency when q-switched are strongly influenced by the unsaturable loss of the saturable absorber. It will be seen that experimentally, the Nd-based lasers are more efficient in q-switched operation.

Row thirteen of Table 1 indicates that two of the materials – Nd:YVO_4 and Yb:Er:YAB – are highly anisotropic in their absorption and emission characteristics. This means that their output laser beam is naturally well polarized, which is advantageous. A negative factor is that their pump absorption is much stronger for one polarization than another, which means that for best efficiency the pump must be polarized, which is an added design constraint. Nd:YAG can be pumped by an unpolarized source without penalty, but unless polarizing optics are added to the laser resonator, the laser output will be in an indeterminant polarization state.

When short pulses and high repetition rates are desired, it is beneficial to confine the gain to a small volume within the gain element. Absorption within a short distance and a small pumped cross-sectional area enable high gain in a shorter laser resonator, resulting in shorter pulses. Row fourteen of Table 1 shows the 1/e absorption depth of the three materials, for the doping level of row one. It is seen that Nd:YVO_4 can absorb pump light in a short distance, less than 1 millimeter. Yb:Er:YAB has absorption almost as strong, and over a wider range of wavelengths. Nd:YAG has the weakest pump absorption.

When pump light is absorbed in a small volume, heating per unit volume is high, since waste heat is concentrated in the small volume. A high thermal conductivity is desirable, since for a given amount of heat dissipation a smaller temperature rise will result. Row fifteen of Table 1 tabulates thermal conductivity of the three materials. Nd:YAG has the best thermal conductivity, Nd:YVO_4 the worst, and Yb:Er:YAB has an intermediate value. The temperature rise in the lasers described in this paper can be large. The temperature of the center of the Nd:YVO_4 lasers rises more than 200 C above that of its surroundings during laser operation. For our Nd:YVO_4 lasers and for some of the Yb:Er:YAB lasers referenced in this paper, the laser material was optically contacted with a sapphire heat spreader in order to avoid unacceptable thermal beam distortion and material fracture. For Nd:YAG such measures are not needed below the 10-watt pump level, partly because of the better thermal conductivity but primarily because the reduced pump absorption makes it impossible to reach the very high heat generation per unit volume of the other two materials.

The choice of a material system for a given application will be determined by the specific requirements. If a high repetition rate and short pulses are required simultaneously, but moderate pulse energy and average power are acceptable, then Nd:YVO_4 is preferred. If high average power is needed, the good thermal conductivity of Nd:YAG may make it the preferred choice. Yb:Er:YAB provides high pulse energy, and enables the use of the most powerful and readily sourced pump lasers.

An important criterion in material selection will be overall efficiency. Though the three materials have similar cw efficiency, it will be seen from the cases described below that the Nd lasers are more efficient in passively q-switched operation. We do not provide an analysis of q-switched efficiency here, but the two determinants of efficiency (beyond cw efficiency) are the unsaturable losses of the q-switching material, which are significant and poorly characterized for both options, and the cross-section lifetime product, which enables laser operation well above threshold, where efficiency is good. The second criteria favor Nd-based lasers relative to Er-based lasers.

3. 500 kHz Nd:YVO$_4$ LASERS WITH >1W AVERAGE POWER

3.1 Experimental Setup

Figure 2 is a schematic diagram of the Nd:YVO$_4$ lasers we built and characterized. The q-switched laser resonator has two components – the Nd:YVO$_4$ gain crystal and the V:YAG saturable absorber, which acts as a passive q-switch. The gain element has a highly reflecting resonator mirror on its outward facing surface. The inward facing, intracavity surfaces of the gain element and the saturable absorber are anti-reflection coated at the lasing wavelength. The output coupler is the outward facing surface of the saturable absorber.

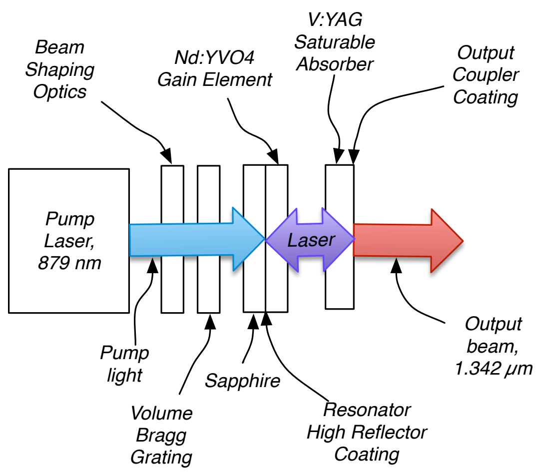

Figure 2. Schematic diagram of laser. The overall resonator was never more than 5 mm in length. The transverse dimensions of parts were about 5 mm x 5 mm, but smaller is possible, as the beams are typically approximately 0.1 mm in diameter.

A piece of sapphire (Al_2O_3) was optically contacted with the Nd:YVO$_4$ in order to create a low thermal resistance path for the heat created by pumping, and thus reduce the maximum temperature rise in the gain element. The sapphire was outside of the laser resonator.

This type of laser has been termed a "microchip" laser[1] because the laser components are small and have only planar surfaces. In our laboratory work, both the gain element and saturable absorber are flat plates with a cross-sectional area of approximately 5 mm x 5 mm. In a product, smaller cross-sectional dimensions are possible, keeping the cost of components low. The thickness of the Nd:YVO$_4$ gain element was 2 mm and the doping was 1%.

V:YAG was provided by Crytur, Ltd. of Turnov, Czech Republic. The three equivalent [100] axes of the V:YAG were oriented normal to the faces and the edges of the parts so that one of these axes is parallel to the polarization of the q-switched laser, as is preferable. The unsaturated absorptivity of the V:YAG at the wavelength of 1342 nm was 1.6 cm^{-1}.

The pump was a single-emitter, wide-stripe diode having an emission width of 200 μm and a rated output power of 10 Watts. A volume Bragg grating stabilized the pump wavelength at 879 nm.

Figure 3 is an annotated photograph of a breadboard laser using the optical arrangement described above. The pump laser, beam shaping optics, volume Bragg grating, and passively-q-switched laser are all mounted on a temperature-controlled base plate. The pump laser output is collimated by a fast axis collimating lens (not visible in Figure 3) positioned adjacent the emitting aperture of the pump laser diode. The wavelength stabilization grating is placed adjacent the fast axis collimating lens. In Figure 3 a single 5.5 mm focal length lens is used to focus the pump light into the gain element (not visible in Figure 3) of the passively q-switched resonator. Other lens positions and arrangement were also used to focus the pump light into the gain element, allowing optimization of the size of the pump volume. The output coupler is on a face of the saturable absorber (not visible in Figure 3) which is glued on an end of a hollow pedestal of a mirror mount that enables angular adjustment of the output coupler so that the passively-q-switched resonator can be aligned. The orientation of the pedestal may be adjusted using four adjustment screws that each elastically compress an associated aluminum cylinder to provide the required angular adjustment. The breadboard laser shown in Figure 3 is portable and has been used in field demonstrations of the laser. No attempt was made to minimize the size of the laser. We anticipate that in a product, the size of the laser could be approximately one or two cubic centimeters.

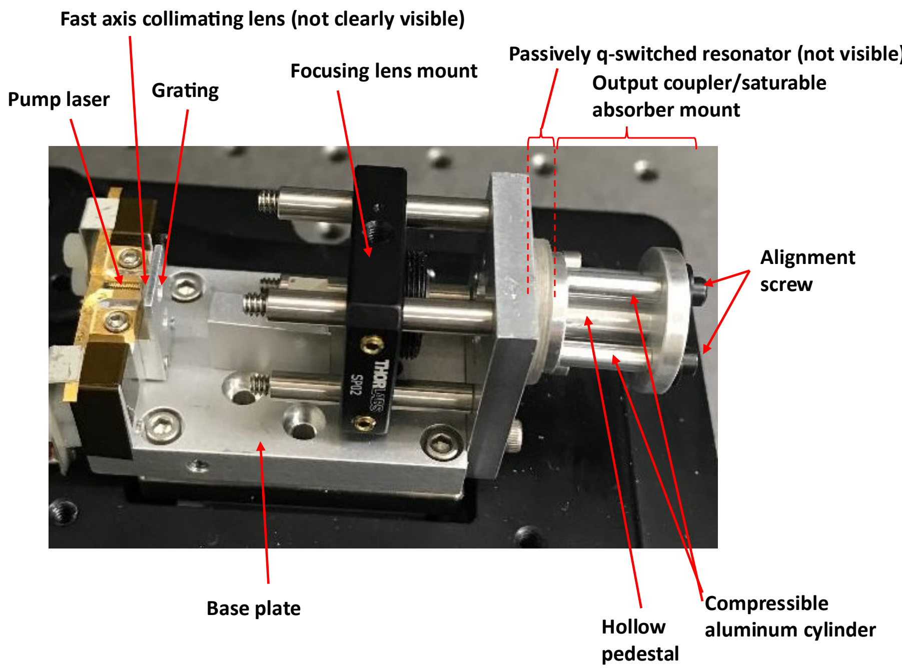

Figure 3. Photograph of breadboard passively-q-switched laser. The length of the full assembly is 7 cm.

3.2 Experimental Results

For the $Nd:YVO_4$ gain elements our work was directed towards operating the passively q-switched laser at a pulse frequency of approximately 500 kHz with pulse energies of several μJ. Such a pulse frequency will enable a LIDAR system to generate 50,000 points in a point cloud at a 10 Hz refresh rate and detect objects at several hundred meters. Such a LIDAR system can be used to determine objects over a relatively wide field-of-view.

Two different laser configurations were evaluated, denoted as laser #1 and laser #2. Table 2 summarizes the results obtained with both lasers, and compares our results with published results from an Yb:Er:YAB passively-q-switched laser optimized for high repetition rate operation. Most terms in Table 2 are self-explanatory. One term that may require some explanation is the term "Energy/duration," defined as pulse energy divided by pulse duration. This is tabulated because it is an easily calculated figure of merit closely related to peak power. Tabulating peak power can be misleading, since the peak power is highly dependent on the pulse profile and may be less important in LIDAR applications than the energy/duration value.

Table 2. High repetition rate experimental performance data from $Nd:YVO_4$ and Yb:Er:YAB lasers.

Parameter	**#1: $Nd:YVO_4$ optimized for short pulses**	**#2: $Nd:YVO_4$ optimized for efficiency**	**Yb:Er:YAB cw pumped *Ref [12]***	**Yb:Er:YAB qcw, 100 Hz, 20% duty cycle**
Lasing wavelength	1342 nm		1548 nm	1553 nm
Pump wavelength	879 nm		976 nm	
Output coupling	25%		6%	
Saturable absorber thickness	0.5 mm	0.4 mm	1.3 mm	
Unsaturated loss, single-pass	8%	6.4%	4.2%	
Pulse duration, FWHM	2.0 nsec	4.2 nsec	8.0 nsec	8.3 nsec
Pulse repetition rate	501 kHz	516 kHz	144 kHz	544 kHz (burst)
Pulse energy	2.45 μJ	2.82 μJ	1.7 μJ	3.9 μJ
Average output power	1.23 W	1.45 W	0.24 W	0.42 W*
Energy/duration	1.23 kW	0.68 kW	0.21 kW	0.47 kW
Pump power	5.87 W	4.44 W	6.3 W	20 W (4 W avg.)
Optical-to-optical efficiency	20.9%	32.8%	3.9%	10.6%

* The average power for the qcw Yb:Er:YAB laser is the average power of 2.1 W during a pulse burst multiplied by the duty cycle of 20%.

Laser #1 used a 0.5 mm thick piece of V:YAG as the saturable absorber. The output coupler was 25% transmitting at the lasing wavelength. The air gap between the gain element and saturable absorber was 2 mm, yielding an overall cavity length of 4.5 mm. This configuration provided 2.0 nsec pulses and an optical-to-optical efficiency of 20.9%. Pulse energy was 2.45 μJ at a repetition rate of 501 kHz, yielding an average power of 1.23 watts.

For laser #2, our goal was to improve efficiency at the sacrifice of pulse width. Efficiency was improved by using a thinner saturable absorber, a 0.4 mm thick piece of V:YAG. This change would be expected to increase pulse repetition rate and reduce pulse energy. To maintain a roughly equivalent pulse repetition rate and pulse energy, we expanded the pump beam cross-sectional area, which increased the lasing mode diameter. To maintain TEM_{00} mode operation, we increased the resonator length to 5 mm. The increased resonator length and the reduced V:YAG thickness resulted in a pulse duration of 4.2 nsec, but at significantly improved efficiency compared to laser #1. There was also a small increase in pulse energy and repetition rate.

The improvement in efficiency of laser #2 is due to a thinner V:YAG as compared to laser #1. In an ideal saturable absorber, its thickness would have a small effect on laser efficiency. Poorly understood loss mechanisms exist in V:YAG.

The last two columns of Table 2 compare our results with those from a Yb:Er:YAB passively q-switched laser optimized for high repetition rate operation. The column second from the right shows results from a cw-pumped laser. All parameters are inferior to those of the $Nd:YVO_4$ lasers. The far-right column contains results for a laser pumped at a high power of 20 watts, but with a 20% duty cycle. The 20% duty cycle allows the laser to operate well above threshold, where it can be more efficient, while keeping the thermal effect of the high pump power at a tolerable level. Much improved performance was obtained, but in a laser of limited utility, since the pulses come in 2 msec bursts separated by 8 msec gaps.

Figure 4 shows repetition rate and average power as a function of pump power for Laser #2 of Table 2.

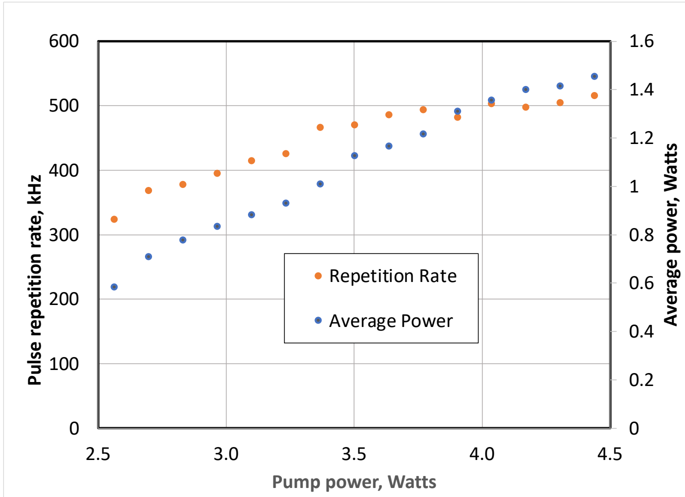

Figure 4. Graph showing the average power and pulse repetition rate of $Nd:YVO_4$ laser #2 as a function of pump power

4. Nd:YAG LASERS

Nd:YAG has a lower lasing cross-section than $Nd:YVO_4$. This will result in passively q-switched lasers with higher pulse energy and lower repetition rate. Nd:YAG also has lower pump absorption, which will lead to a larger pumped volume, which also pushes performance toward higher pulse energy and lower repetition rate.

It will be seen that Nd:YAG and Yb:Er:YAB enable similar performance, but with an efficiency advantage for Nd:YAG.

4.1 Experimental Setup

Figure 5 is a schematic of the Nd:YAG lasers we built and characterized. Changes from the $Nd:YVO_4$ design are:

- To improve pump absorption, a coating having high reflectivity at the pump wavelength was placed on the interior surface of the gain element, so that the pump can double-pass the Nd:YAG. This coating has the secondary purpose of keeping unabsorbed pump light out of the V:YAG, where its presence is undesirable.
- To increase pump absorption, the crystal length was increased to 3 mm. The doping level was 0.8%.
- To avoid destabilizing feedback to the pump diode from the aforementioned pump high reflector, the pump beam is misaligned in angle from the axis of the laser resonator. The angle in Figure 5 is exaggerated for clarity.
- The sapphire heat spreader is eliminated.

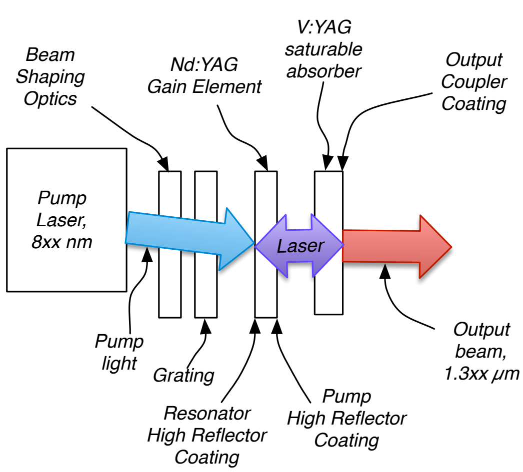

Figure 5. Schematic diagram of Nd:YAG lasers.

4.2 CW pumped Nd:YAG lasers

We built a wide variety of cw-pumped Nd:YAG passively q-switched lasers. Table 3 presents two extreme cases. Performance intermediate between these cases was also demonstrated.

The first laser presented below, designated laser #3, was optimized for short pulses. A thick piece of V:YAG was used, and pulses of duration 1.4 nsec resulted at 23 kHz repetition rate and 14.8 µJ pulse energy. Efficiency was 9.5%. The case presented as laser #4 shows the other extreme – 5 nsec pulses at a 160 kHz repetition rate and 5.9 µJ pulse energy. Laser #4 had a much higher efficiency of 22.9%. The shift in pump wavelength from 869 nm to 808 nm was one contributor to improved efficiency, but by far the main reason is the use of the shorter piece of V:YAG.

A notable aspect of the Nd:YAG performance is the presence of two wavelengths, 1319 nm and 1338 nm. Any given pulse is at one wavelength or the other – the laser alternates wavelength on alternate pulses. A laser designed with a selective coating could eliminate this issue at no loss in efficiency.

In Table 3 the performance of the Er-based lasers is competitive in pulse energy and repetition rate to the Nd-based lasers, but the Er-based lasers have a substantially longer pulse duration. Except for the extremely short pulse case of laser #3 the Nd:YAG lasers were more efficient.

Table 3. Experimental performance data from cw-pumped Nd:YAG, Yb:Er:GdAB and Yb:Er:YAB lasers

Parameter	**#3: Nd:YAG short pulses**	**#4: Nd:YAG efficiency**	**Yb:Er:GdAB** ***Ref [13]***	**Yb:Er:YAB** ***Ref [3]***
Lasing wavelength	1319 nm, 1338 nm		1550 nm	1553 nm
Pump wavelength	869 nm	808 nm	976 nm	
Output coupling	25%	15%	6%	2.5%
Saturable absorber thickness	0.6 mm	0.3 mm	0.75 mm	1 mm
Unsaturated loss, single-pass	9.6%	4.8%	1.5%	3%
Pulse duration, FWHM	1.4 nsec	5.0 nsec	12 nsec	7 nsec
Pulse repetition rate	23 kHz	160 kHz	32 kHz	77 kHz
Pulse energy	14.8 µJ	5.9 µJ	18.7 µJ	10 µJ
Average output power	0.34 W	0.94 W	0.60 W	0.77 W
Energy/duration	10.6 kW	1.2 kW	1.6 kW	1.43 kW
Pump power	3.6 W	4.1 W	5.9 W	7.2 W
Optical-to-optical efficiency	9.5%	22.9%	10.1%	10.7%

4.3 Quasi-cw-pumped Nd:YAG Lasers

The goal of our final experiment was maximizing pulse energy, without regard to efficiency. This entailed:

- Using a laser material with a relatively small lasing cross-section, such as Nd:YAG,
- Using the thickest available V:YAG saturable absorber,
- Increasing pump beam diameter,
- Quasi-cw (qcw) pumping.

The advantage of qcw pumping is that it reduces thermal effects in the laser. In Nd:YAG, the absolute temperature itself is not a problem, but the induced thermal lens can cause the resonator mode to become too small for high pulse energy operation. With the reduction in thermal lensing resulting from qcw pumping, a large mode size and thus larger pulse energy can be maintained even with high pump power levels, enabling operation at a higher pulse energy. Our results can be compared to those of Šulc et. al.[14,15]

The repetition rate of the pump pulses was 1 kHz. The duration of the pump pulses was selected so that exactly one q-switched pulse occurred per pump pulse, and it occurred as late as possible in the pump pulse while ensuring a single q-switched pulse. This resulted in a pump duty cycle of 26% and a pump pulse duration of 0.26 msec.

Table 4. Experimental performance data from quasi-cw-pumped Nd:YAG and Yb:Er:LuAB lasers.

Parameter	**#5: Nd:YAG qcw**	**Yb:Er:LuAB qcw** ***Ref [16]***
Laser material	Nd:YAG	Yb,Er:LuAB
Lasing wavelength	1338 nm	1522 nm
Pump wavelength	808 nm	975 nm
Output coupling	15%	15%
Saturable absorber thickness	0.6 mm	1.55 mm
Unsaturated loss, single-pass	9.6%	11%
Q-switched pulse duration	1.8 nsec	1.9 nsec
Repetition rate	1000 Hertz	100 Hertz
Pulse energy	40 μJ	48.3 μJ
Average output power	40 mW	4.8 mW
Energy/duration	22.7 kW	25.4 kW
Pump power (while on)	4.3 W	24.6 W
Pump duty cycle	26%	5%
Pump power (average)	1.1 W	1.2 W
Pump pulse duration	0.26 msec	0.50 msec
Optical-to-optical efficiency	3.8%	0.4%

Pulse energy is a performance parameter for which Er-based laser may have an advantage, since the low lasing cross-section allows greater energy storage. Yet the two materials have similar pulse energies and pulse durations, with the Nd laser having an order of magnitude higher repetition rate and efficiency, which is to say, about ten times more output with roughly the same input.

Figure 6 shows the temporal shape of the laser pulse of laser #5. Note that the peak power of 16 kW is about 70% of the "Energy / duration" value tabulated. This ratio is typical of the lasers described in this paper.

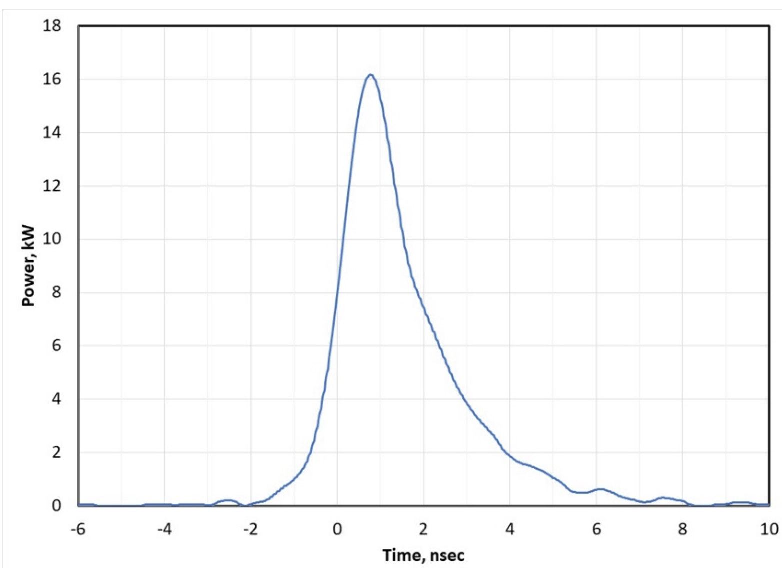

Figure 6. Temporal shape of a pulse from a quasi-cw-pumped Nd:YAG laser operating at 1 kHz.

4.4 Pulse statistics and beam quality

The quasi-cw-pumped Nd:YAG laser of Table 4 lased at a single wavelength, 1338 nm, and the pulse energies of each pulse in the pulse train were equal within 1%. This consistency in pulses was not the case for the other lasers reported in this paper. The other lasers had pulse energies, and intervals between pulses, varying by about 20%. This variation is due to the laser operating on multiple axial modes. Each individual pulse lases with a single axial mode. Some axial modes are closer to the wavelength of peak gain, and pulses operating on such a high-gain mode will have lower energy and a smaller preceding pulse interval. The reason for multi-axial-mode operation of the laser is spatial hole burning. No single axial mode can extract all the energy stored because of this effect. Successive pulses will operate on different axial modes in order to extract energy from regions where previous pulses had standing wave nulls.

The quasi-cw-pumped laser had no such mode competition because the time between pulses was long compared to the upper state lifetime of the excited state. (See row 6 of Table 1.) Any residual energy left behind in the nulls of the highest-gain mode will have decayed before the next pulse occurs.

This observation that individual pulses correspond to individual modes of the laser resonator also applies when the laser is operating with multiple transverse modes, also known as spatial modes. Spatial modes other than TEM_{00} are undesirable because beam quality is degraded when these modes exist. It is easy to tell when a passively q-switched laser is operating with higher-order spatial modes. There will be pulses present which are drastically different from the TEM_{00} pulses in both beam shape and amplitude. When these higher order modes are only slightly above threshold, the higher order mode pulses will appear just a few pulse widths delayed from the TEM_{00} pulse, but when they are well above threshold, they are well separated from the TEM_{00} mode pulses. If a small aperture detector, or an optical fiber connected to a detector, is translated laterally within the laser beam, the ratio of the pulse amplitudes between the TEM_{00} pulses and the multimode pulses will change. Thus, by observing pulse statistics while moving the detector, one can verify TEM_{00} laser operation. All lasers we report and tabulate in this paper only operate in the TEM_{00} mode. While we did not measure the beam quality in all cases, all measured cases had $M^2<1.2$.

5. CONCLUSIONS

Passively q-switched lasers based on semiconductor-laser-pumping of $Nd:YVO_4$ and Nd:YAG provide nanosecond pulses at a wavelength near 1.3 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 1.3 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 lasers operating at wavelengths between 800 and 900 nm can be used as the pump source.

We demonstrated a q-switched laser with $Nd:YVO_4$ having an average power of 1.45 W using 4.5 W (optical) of pump power. This laser operated at a repetition rate of 515 kHz and pulse duration of 4.6 nsec FWHM. Peak power was about 500 W. In a different configuration, with a thicker piece of V:YAG and a higher pump power, the laser operated with 1.23 W of average power at a 501 kHz pulse repetition rate with 2.0 nsec pulses. The peak power was almost 1 kW. Both lasers were diffraction-limited and operated at a wavelength of 1.342 µm.

We also demonstrated passively-q-switched lasers with Nd:YAG as the gain material. Nd:YAG has a lower lasing cross-section than $Nd:YVO_4$ enabling q-switched pulses having a higher pulse energy, albeit at a lower pulse repetition rate. We demonstrated a variety of Nd:YAG lasers having pulse energies from 5.9 µJ to 40 µJ, pulse duration from 1.4 nsec to 5 nsec, and pulse repetition rates from 1 kHz to 160 kHz. The lasers were diffraction-limited, with wavelengths of 1.319 µm and 1.338 µm.

The optical-to-optical efficiencies of these lasers varied from 3.8% to 32.8%. Higher efficiency was observed in lasers with higher repetition rates and longer pulse durations. The key parameters that were adjusted to get the reported range of performance were the thickness of the V:YAG and the size of the pumped region in the gain element. By adjusting these parameters, lasers filling the range between the extreme cases can be readily produced.

We compared our results with a competing eye-safe laser technology, passively q-switched lasers based on erbium doped materials and lasing in the slightly less eye-safe wavelength band of 1.5-1.6 µm. Published reports on these lasers show that they have longer pulses for equivalent pulse repetition rates, and lower efficiency. The maximum obtainable pulse energy is similar for the Er-based lasers and Nd:YAG. When both short pulses and high repetition rates are needed $Nd:YVO_4$ is far superior to both Er-based lasers and Nd:YAG lasers due to its high gain cross section and strong pump absorption.

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