

High-energy Q-switched 0.946- μm solid-state diode pumped laser

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Designing a high-energy Q-switched all-solid-state laser operating on the quasi-four-level 0.946- μm transition of Nd:YAG is quite challenging because of intense competition from the high-gain 1.064- μm transition. We have achieved such a laser by implementing an innovative resonator design, augmented by specialty coatings. Utilizing this approach, we obtained >75 mJ of Q-switched TEM₀₀ mode energy in an all-solid-state diode pumped laser, a factor of 22 times more energy per pulse than any published data have reported. © 2002 Optical Society of America

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1. INTRODUCTION

Researchers^{1–3} have reported diode pumped all-solid-state laser operation at 0.946 μm by use of the $R_1 \rightarrow Z_5$ line of the ${}^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition in Nd:Y₃Al₅O₁₂ (Nd:YAG), but only a limited amount of energy has been generated. With this novel approach, we have obtained a factor-of-22 times more energy per pulse than has been reported in any other published data for diode pumped lasers. A high-energy pulsed laser operating on this transition would be extremely useful to the remote-sensing scientific community in view of the presence of strong atmospheric water-vapor absorption lines near 0.946 μm .⁴ The 0.946- μm laser output energy can also be frequency doubled to produce blue light, which would be useful for optical memory and high-density data storage applications as well as in underwater transmission. The same laser could also be frequency tripled to produce ~0.315- μm light, which would be useful as one of the sideline wavelengths for the remote sensing of ozone in the atmosphere.

A laser operating near 0.94 μm would provide more-accurate measurements of water-vapor concentrations, especially in regions of low water density, than were made previously. Currently, injection-seeded Ti:Al₂O₃ lasers exist that are being used to measure H₂O concentrations in the atmosphere near 0.820 μm .⁵ A 0.94- μm laser would be significantly better than a 0.820- μm laser because the water-absorption lines near 0.94 μm are approximately 30 times stronger than those near 0.820 μm . Additionally, both of the wavelengths that would be needed for a differential absorption lidar system are obtainable by tuning of the seed laser instead of relying on frequency conversion techniques. A directly pumped solid-state laser would be simple, reliable, and robust, making it ideal for remote operations, such as in space, where maintenance would be expensive and difficult.

There are several obstacles present in the quest for such a laser. First, in Nd-doped materials the 0.94- μm $R_1 \rightarrow Z_5$ line of the ${}^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition is a quasi-four-level transition that competes with the much stronger $R_2 \rightarrow Y_3$ line of the ${}^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition at 1.064 μm . The 0.94- μm transition terminates in the ground-state manifold, which has a significant thermal population at room temperature. The pumping must be sufficiently strong to overcome the population in the lower laser level, thereby increasing the threshold energy for laser operation. In addition, the lower laser level population allows for ground-state reabsorption of the laser light, decreasing the overall performance of the laser. Second, the 0.94- μm transition has a much smaller stimulated-emission cross section than the transition at 1.064 μm . It is thus necessary to design a 0.94- μm laser that discriminates against the detrimental effects of the high gain at 1.064 μm . One such effect is amplified spontaneous emission (ASE).^{6,7} ASE is not a serious problem in normal mode operation, as the gain can be maintained at moderate levels. ASE becomes a problem when the laser is Q-switched as the gain reaches high levels during hold-off and is manifest as a sublinear roll-off in laser energy with increasing pump energy.

2. EXPERIMENTAL SETUP

The experiments described here employ a folded laser resonator that permits a quadruple pass gain within each rod. The round-trip length for a single-module resonator is 3.352 m; it doubles to 6.704 m for a two-module resonator; and it triples to 10.06 m for the three-module resonator shown in Fig. 1. This long length is necessary for good overlap between the pumped volume in the crystal and the TEM₀₀ mode volume of the resonator. This laser has been designed to be modular and compact, making it

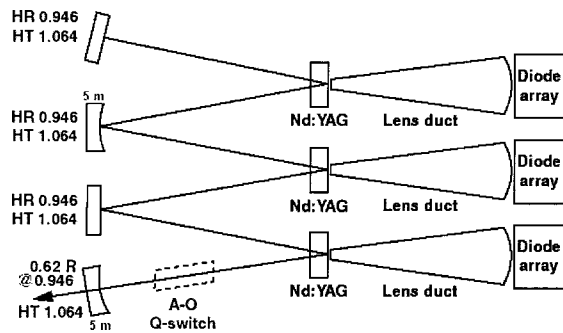


Fig. 1. Experimental setup with multiple modules for high energy.

easy to use and expand. Each module is assembled individually on a 1/2-in. (1.27-cm) thick optical breadboard that is 3 in. wide by 10 in. long and consists of a conductively cooled laser diode array mounted upon a copper plate, which is in turn mounted upon a brass water-cooled heat dump block; a beam converter (lens duct) upon a five-axis translation stage; and a Nd:YAG laser crystal at ambient temperature.

The experiments described here employ an end-pumped, *Q*-switched laser that was designed and demonstrated previously at the NASA Langley Research Center as part of a doctoral program with the University of Arizona.⁸ In that research the folded oscillator configuration, the diode array stack, the lens duct, and the laser rod parameters were designed to yield optimum performance at the 0.946- μm transition. The experiments reported here use the identical laser gain module with a longer folded resonator that employs different combinations of output couplers and end mirrors. After repeating the initial experiments and corroborating the results with a single module these experiments go further by incorporating additional gain modules in the resonator. They demonstrate how the performance of the 0.946- μm Nd:YAG laser scales with the number of gain modules.

Each of the conductively cooled laser diode arrays that are used as pump sources for the Nd:YAG laser crystals is a stack of 30 individually microlensed 100-W diode bars, with a bar-to-bar spacing of 800 μm . The arrays are conductively cooled to be acceptable for space-based applications. Each array has a spectral width of 3 nm and is temperature tuned via a thermoelectric cooler to a center wavelength of 0.807 μm to correspond to the peak absorption of Nd:YAG. The beam divergence of the fast axis of each array (perpendicular to the active region) is less than or equal to 3°, and the beam divergence of the slow axis of each array (parallel to the active region) is less than or equal to 10°. The output of each array is collected by a lens duct, which is antireflection coated for the diode pump wavelength of 0.807 μm . Approximately 80% of the diode energy is transmitted through the lens duct. We consider the transmitted energy to be the pump energy for our experiments. The lens duct focuses the diode array's output energy in a 2-mm-diameter flat-to-flat octagonal pump area in the laser crystal.⁸ The use of a high-brightness pump is important to overcome limitations that are intrinsic to efficient, low-threshold operation. The presence of both high pump brightness and short gain elements is necessitated by the relatively low-

emission cross section and the potential for significant ground-state absorption at the laser wavelength because the terminal laser level is thermally populated. It is thus necessary to maximize the absorption of the pump in the laser rod while minimizing the path length of the rod to prevent ground-state absorption. Using shorter rods helps to minimize reabsorption loss of the 0.946- μm laser emission as well as the effects of ASE. The laser crystals are 1% Nd:YAG rods that are 4 mm long.⁸

Special coatings⁸ have been developed to mitigate energy storage problems including parasitic lasing and ASE and to encourage the resonator to operate at the lower gain transition at 0.946 μm . The coating on the pumped surface is highly transmitting at the pump wavelength of 0.807 μm and at 1.064 μm and is highly reflecting at a laser wavelength of 0.946 μm . The other surface is coated to be antireflective at both 0.946 and 1.064 μm and will promote *Q*-switched lasing by sending some of the ASE outside the resonator. Dichroic mirrors are coated to be highly reflecting at 0.946 μm and highly transmitting at 1.064 μm ; this encourages lasing on the weaker 0.946- μm transition while discouraging oscillation and parasitic lasing at 1.064 μm . Other techniques employed to suppress the 1.064- μm transition are the use of short rod lengths and insertion of each rod into a Sm-doped glass tube to absorb any 1.064- μm emission.⁸

Optimized pump geometry is important. We use an end-pumping geometry in our resonator. It permits better overlap between the pumped volume of the laser rod and the laser mode volume than do other pumping geometries, leading to higher efficiencies and lower threshold energies.

In designing this resonator we wrote a model in Mathcad, utilizing the *ABCD* matrix approach.⁹ This model permits the optimization of the resonator length and the mirrors used within the resonator (i.e., their radii of curvature and position). These parameters are optimized for the resonator to maintain a beam diameter of approximately 2 mm at each laser crystal such that the beam size coincides with the size of the pumped volume of the laser crystal.

3. LASER PERFORMANCE

Laser performance was evaluated for three configurations, a single-module resonator, a two-module resonator,^{10,11} and a three-module resonator. For all configurations, each laser diode array was pumped for 160 μs at a pulse repetition rate of 1 Hz. The laser diode array's drive pulse was obtained from a digital delay generator. All diode drivers were designed and manufactured in house, and the power supplies were obtained commercially.

A single module was built and evaluated. It consisted of a single laser gain module, a 10-m curved dichroic end mirror (highly reflecting at 0.946 μm and highly transmitting at 1.064 μm), and a flat output coupler mirror (highly transmitting at 1.064 μm). The low reflectivity at 1.064 μm of both mirrors and the Nd:YAG crystal promotes laser operation at the 0.946- μm transition, and the use of a 0.94- μm bandpass filter in front of the detector verifies laser operation at the 0.946- μm transition. This

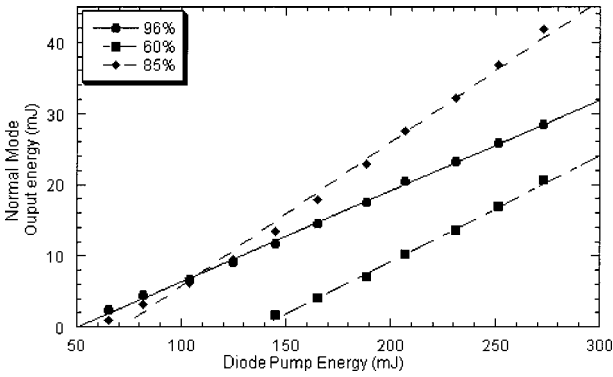


Fig. 2. Typical normal mode energy results for a series of output couplers in a single-module resonator.

resonator was made to lase with a series of output coupler mirrors in normal mode. To evaluate laser performance in the Q -switched mode we inserted an acousto-optic fused-silica Q switch into the resonator between the laser crystal and the output coupler, setting it to switch the pulse out of the resonator 5 μ s after the end of the diode pump pulse. A high-speed detector was used to measure the pulse length, which was on average 75 ns. The laser output energy versus input optical pump energy data for both the normal mode and the Q -switched mode were fitted to a straight line to yield the optical-to-optical slope efficiency and the threshold energy for laser operation. Typical ratios of input pump energy to output laser energy are shown in Fig. 2 for the series of output couplers tested. The results shown are for normal mode operation. The best performance obtained at $0.946 \mu\text{m}$ with a single laser gain module in the resonator was approximately 45 mJ of normal mode laser energy and 26 mJ of Q -switched laser energy for a pump energy of 231 mJ.

In an effort to increase the amount of available laser energy at $0.946 \mu\text{m}$ we added a second gain module to the resonator. The addition of a second laser gain module doubled the gain within the resonator. An additional dichroic folding mirror was added between the two laser gain modules, forming an M-shaped resonator. This mirror was also highly reflecting at $0.946 \mu\text{m}$ and highly transmitting at $1.064 \mu\text{m}$. The 10-m curved end mirror was then repositioned to form a symmetrical resonator. The two-module resonator was evaluated with a series of output couplers. Linear fits of these data yielded optical-to-optical slope efficiency and laser operation threshold energy. Both the slope efficiency and the threshold energy are plotted as functions of the negative logarithm of the output coupler mirror's reflectivity in Fig. 3. The threshold energy can be adequately fitted with a straight line:

$$E_{\text{PTH}} = m \ln(R_M) + E_{\text{PTHO}}, \quad (1)$$

where E_{PTH} is the pump energy threshold, E_{PTHO} is the threshold at unity mirror reflectivity, and R_M is the output coupler mirror's reflectivity. The slope efficiency may be fitted to

$$\sigma_s = \sigma_{\text{sm}} \ln(R_M) / \ln(R_M R_L), \quad (2)$$

where σ_s is the slope efficiency, σ_{sm} is the maximum slope efficiency, R_M is the output coupler's reflectivity, and R_L is

other resonator losses. This fit provides the theoretical maximum slope efficiency that can be obtained from the resonator. The theoretical curve fit suggests that the maximum slope efficiency obtainable is 0.2319 ± 0.0086 . As in the single-module resonator, the experimentally obtained slope efficiency is greater than that predicted by the theoretical curve fit, though it is within experimental error. By doubling the number of laser gain modules in the resonator we were able to double the amount of normal mode energy available from the laser. This result is significant, as it demonstrates that the normal mode laser output energy scales approximately with the number of gain modules. The Q -switched energy increased, although a roll-over that suggested the presence of ASE was observed. Evaluation of this resonator configuration by use of the $ABCD$ matrix approach predicted that the beam diameter would be equal to the pumped volume in both of the crystals and that the resonator would be stable if 5-m curved mirrors were used as the end mirror and the output coupler. This prediction was experimentally verified. The most energy was produced by use of this combination of mirrors. Thus there is good overlap between the pumped volume in the crystal and the mode volume of the resonator.

To further increase the laser's output energy we then added a third laser gain module to the resonator. Evaluation by the $ABCD$ matrix approach suggested that the resonator would be stable with this combination of mirrors: a 5-m curved output coupler, a flat folding mirror, a 5-m curved folding mirror, and a flat end mirror. Normal mode operation produced >150 mJ of energy with an optical-to-optical slope efficiency of 0.205, and Q -switched operation yielded ≥ 75 mJ with an optical-to-optical slope efficiency of 0.091. The normal mode energy obtained is a factor of 11 greater than previously reported in the literature, and the Q -switched energy is a factor of 22 greater than reported.³ This increased output energy continues the trend that was observed for the two-module resonator. Figures 4 and 5, respectively, show the comparisons for normal mode and Q -switched operation. They also show that tripling the number of laser gain modules within the resonator also approximately triples the total laser output energy. In this manner it should be possible to increase the total laser energy output by adding additional gain modules to the resonator.

The single-module resonator has an optical slope efficiency of 0.288, the two-module resonator has an optical

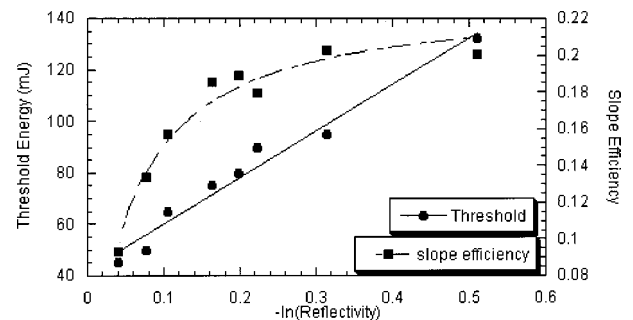


Fig. 3. Two-module resonator evaluation using data obtained in normal mode operation [slope efficiency and threshold versus $-\ln(R_M)$].

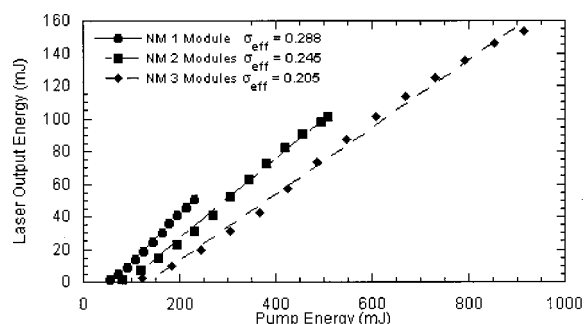


Fig. 4. Normal mode energy comparison for three resonator configurations.

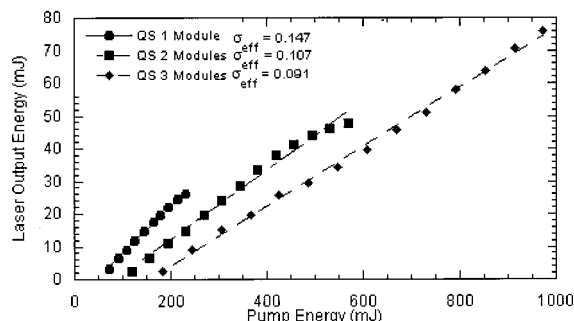


Fig. 5. Q-switched energy comparison for three resonator configurations.

slope efficiency of 0.245, and the three-module resonator has an optical slope efficiency of 0.205. The difference in the three slope efficiencies may be attributed to the additional losses that are incorporated into the resonator as additional reflecting surfaces are added. Additionally, an increase in laser threshold energy is seen as the number of laser gain modules is increased. This makes sense because, with each additional gain medium within the resonator, more pump energy is required for optical transparency to be attained.

All three resonator configurations operated in TEM₀₀ mode, and the output beam was ~ 1.3 times the diffraction limit. We measured the beam in the near and far fields, using a camera and beam analysis software. Beam quality is defined as $\pi\omega_0\omega_f/f\lambda$, where ω_0 and ω_f are the beam radii in the near and the far fields, respectively, of a lens with focal length f . Having a good-quality output beam will facilitate frequency conversion, yielding higher efficiencies.

4. CONCLUSIONS

We have taken a unique approach to the challenge of obtaining high energy at 0.946 μm , producing >150 mJ of normal mode energy and >75 mJ Q-switched energy. This energy was generated by use of three diode pumped gain modules in an innovative resonator design. This approach is somewhat different from the usual one. To

date, with this approach we have far exceeded the normal mode energy available at 0.946 μm by a factor of 11 and the Q-switched energy by a factor of 22 compared with those of current systems reported in literature. We have analyzed the resonator design in an effort to build a high-power, high-efficiency 0.946- μm laser. This analysis has allowed us optimally to overlap the laser mode volume with the pumped volume in all three crystals. We have employed a creative combination of specialty coatings to encourage this elusive transition to lase. Although we have thus far looked only into tripling the number of laser gain modules and thereby tripling the output energy, results encourage us to believe that we can extrapolate this approach to further increase the laser output energy. Work is currently under way to design and build a pre-amplifier to further increase the energy that can be garnered from this system.

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