4-Pass Pumping of Nd+3:YAG Slabs

D. Barry Coyle

NASA-GSFC, Laboratory for Terrestrial Physics, Greenbelt, MD 20771

Demetrios Poulios

The American University, Dept. of Physics, Washington, DC 20016

A solid-state, side pumping scheme, designed to enhance pump energy absorption, has been adapted for use in small, side-pumped, Nd^{+3}:YAG zigzag lasers. This technique allows for pump radiation to make four complete passes through the gain medium, effectively doubling the absorption length of the usual 2-pass geometry. This produces higher inversion densities, higher gains, broader operating temperature bands and overall higher efficiencies. The improved performance has been demonstrated with a small Nd^{+3}:YAG, mJ-class oscillator, and will aid in the development for space-based remote sensing laser transmitters for altimetry and mapping instruments.

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Introduction:

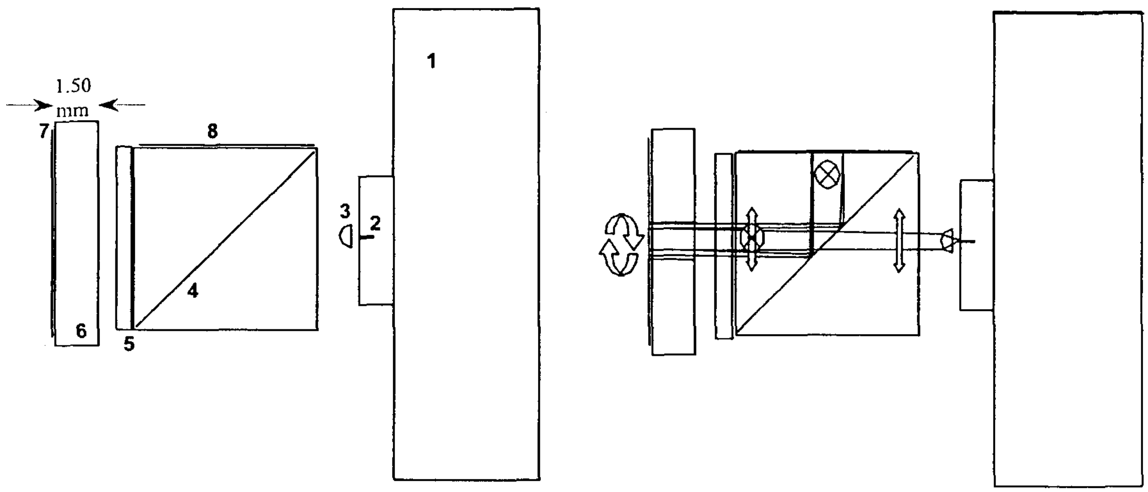
A large portion of NASA-Goddard's in-house research and development effort in laser technology is concentrated in Nd^{+3}:YAG-based transmitters for applications in laser-based remote sensing of earth and planetary surfaces and environments. This article describes a new pumping scheme with Nd:YAG crystals, however it could be applied to almost any solid state laser material. Two factors most critical to the final cost and success of such space-based laser systems are the total electrical-optical efficiency and long-term reliability. Enhancing optical efficiency, (1064 nm laser pulse production)/(809 nm diode pump light), is of particular interest given that previous systems such as the Mars Orbital Laser Altimeter (MOLA), the Geoscience Laser Altimeter System (GLAS or ICEsat), and the recently launched Mercury Laser Altimeter (MLA) all employed pulsed, diode pumped Nd^{+3}:YAG laser transmitters with wall-plug efficiencies of 3% or less.(1,2,3) An increase of only 2% in the overall electrical efficiency of a 2% efficient flight laser altimeter, for example, corresponds to a 100% (2X) improvement in performance. Assuming the pulse energies and repetition rates are held constant for said mission, this new 4% laser system would allow for significant spacecraft mass savings from smaller solar arrays, reduced power bus capacity requirements, and reduced thermal loads and heat removal capacity. Furthermore, the reduced instrument mass, size, and complexity have immediate impacts on mission reliability and total mission costs. We have demonstrated flight laser candidates of >6 % wallplug efficiency through comprehensive system design and optimization efforts.(4,5) There are, however, a number of laser cavity design tradeoffs that make increasing efficiency in side-pumped zigzag slab lasers a nontrivial matter. For example, it often behooves the laser designer to make the slab as thin as possible to minimize thermal gradients, force TEM_{00} operation with no cavity apertures, and optimally match the overlapping volumes between the pumped region and the cavity mode.(6) However, reduction of the slab thickness also decreases the pump absorption length, which can have a negative effect on optical efficiency. Many side-pumped Nd:YAG lasers employ odd or even bounce zigzag slabs dielectrically coated to support 2-pass pumping.[7] It is worthwhile to note that the pump diode array facets are subjected to unabsorbed pump light exiting the crystal with 2-pass pumping, possibly resulting in localized heating effects and a potentially reduced diode lifetime. Thus, the slab must be of a minimum thickness to absorb enough of the pump energy such that no optical damage is done to the diode arrays in the long or short term. This value can be difficult to determine, especially since if differs for each specific laser design. Generally, the thinner the side-pumped laser crystal, the greater amount of unabsorbed pump light strikes the diode arrays.

To circumvent the problem of leftover pump light, a simple diode array side-pumping scheme utilizing polarization manipulation has been developed. This scheme allows the pump radiation to make a total of 4 passes through the same volume of gain medium rather than the customary 2, thereby increasing the pump absorption fraction. Furthermore, the crystal thickness can be reduced to better use the inherent slab aperture to hold the cavity to TEM_{00}. The setup is also compact and mechanically robust, making it suitable for space flight qualification studies. To characterize the performance effects of the 4-pass pumping system, a small Q-switched zigzag slab laser was assembled and tested in both 2-pass and 4-pass configurations. It was found that the 4-pass configuration not only boosted the optical efficiency of the system, but also significantly reduced the sensitivity of the cavity output power to the pump diode temperature.

Experimental:

Our Nd:YAG gain medium used in the experiments was a 12-bounce zigzag slab with a tip angle of 27.5°, a tip-to-tip length of 30.3 mm, an internal path length of 32.8 mm, a pump thickness of 1.5 mm, and a width (or height) of 5.0 mm. We positioned the slab inside a 16 cm long plano-concave cavity with a +4 m radius of curvature (ROC) highly reflective (HR) mirror and 70% reflective flat output coupler. A pair of single-bar, 809 nm laser diode arrays, each rated at 100

W peak output, were used to pump the slab. These arrays were driven at 80 W/bar, pulsed at 100 Hz, with a 200 μs pump pulse length. We used small anti-reflection (AR) coated cylindrical lenses bonded to the array output facets by the manufacturer in order to collimate the 809 nm diode light in the fast axis. The pump beam from each array is directed upon the entrance face of the 4-pass pump coupler (4PPC) optic as shown in Figure 1.



(a) (b)

Fig. 1. Diagram of 4PPC assembly (1a) and the pump light path under operation (1b). Item 1-diode array heat sink, 2-single bar QCW diode array, 3-collimating cylinder lens, 4-right angle polarization surface, 5-¼ waveplate, 6-Nd:YAG zig zag slab, 7- & 8-HR coatings for 809 nm.

A 4PPC consists of a custom-made 2.5 x 2.5 x 14.0 mm^3 rectangular polarizing block where 3 of the 4 rectangular faces are manufactured for optical use. One of these faces is AR coated at 809 nm, one face HR coated at 809 nm, one polished and the final face left unpolished. The square end faces are also left unpolished and are not used optically. The single polished, but uncoated, face is bonded to an AR coated λ/4 waveplate that has been shaped to match the polarizer's rectangular dimensions. The collimated pump light is p-polarized, normal to the diode's fast axis, as it enters the AR face such that it passes unimpeded through the polarizer block, and out through the λ/4 waveplate towards the slab. As the light enters the Nd:YAG, it is now circularly polarized, whereupon a double-pass absorption path is completed through the laser crystal. The returning unabsorbed pump energy is then converted to s-polarization by the λ/4 waveplate, as it re-enters the 4PPC, and proceeds to reflect off the 45° internal polarizing surface. The HR coated surface sends the s-polarized off the 45° surface, and out through the λ/4 waveplate. The remaining pump light becomes circularly polarized again, and is sent into the Nd:YAG slab for another 2 passes of absorption. Any unused energy leaving the slab after 4 passes is conditioned back to p-polarization and directed back to the diode arrays. However, one simply needs to be careful to optimize the slab thickness and diode array operating temperature such that the absorption efficiency is 90% or more to minimize this effect.

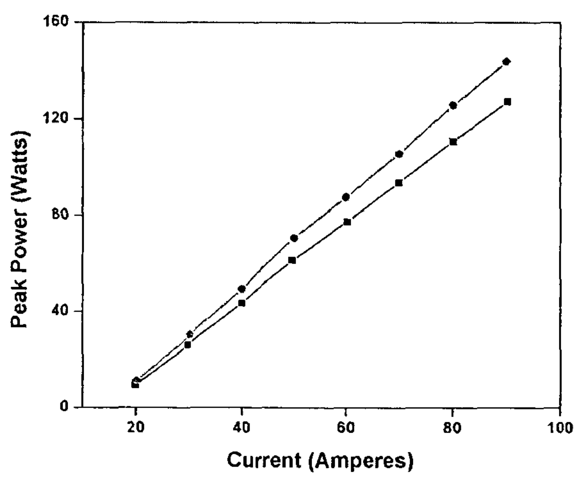


Fig. 2. Total transmitted array peak power striking the Nd:YAG slab vs. diode drive current with (squares) and without (circles) 4PPC optic.

The 4PPC optics do introduce some transmission loss however, Figure 2 shows a comparison between the total peak output powers from the two arrays at various diode currents with and without the 4PPC optics in place. Our prototype 4PPC has a measured p-polarization single-pass transmission loss of ~12%, presumably attributable to visible imperfections in the AR coatings, and the inherent 5% loss at the 45° internal polarizer surface.(8)

Estimates of the peak inversion density achieved in the 2-pass and 4-pass cases were modeled for the peak performance prediction for our experimental setup. This configuration included a pair of single bar, lensed diode arrays, driven at 65A for an output power of 48 W each, 200 μs pump pulses, 100 Hz PRF, and thermally centered on the peak pump wavelength of 809 nm. We measured the power leaving the diode arrays' collimating lenses and call this value the initial diode array's pump power, even though these scatter ~ 5 % of the radiation leaving the semiconductor facets. We assume a simple Beer's Law-type absorption in the gain medium, with an Nd^{+3}:YAG absorption cross-section of $\sigma_{abs} = 3.4 \times 10^{-20}$ cm^3.

We first calculate the absorption efficiency into the Nd:YAG slab for a 2-pass configuration.(9) A pair of lensed, single-bar, diode arrays are close coupled directly to the slab's AR pump face. The pump beam produced is a sheet of 809 nm light and was measured with a CCD to have a $1/e^2$ thickness of 0.8 mm and a width of 22 mm. To calculate the absorbed energy, we assume a Nd:YAG slab coupling efficiency (η_{SC}) of 0.99 into the slab, a color efficiency (η_{CE}) of 0.76, a fluorescence efficiency (η_{Fl}) of 0.67, and a quantum efficiency (η_{QE}) of 0.95. From Beer's Law,

$$E_{out} = E_{in} \cdot e^{(-\sigma_{abs} \cdot N1 \cdot 2 \cdot x)}, \quad (1)$$

where the absorption cross section at 809 nm is $\sigma_{abs} = 3.4 \times 10^{-20}$ cm^{-2}, the ground state Neodyimium ion density for 1.1% Nd:YAG is $N1 = 1.38 \times 10^{20}$ cm^{-3}, and the slab thickness is $x = 0.15$ cm, we find an absorption efficiency of $\eta_{abs} = (E_{in} - E_{out}) \cdot 1/E_{in} = 0.78$.

Using $E_{st} = \eta_{PC}\eta_{CE}\eta_{FI}\eta_{abs}\eta_{QE}E_{LD}$, where the single pump pulse energy entering the slab is $E_{in} = \eta_{PC} E_{LD} = 19.0$ mJ, we find $E_{st} = 7.2$ mJ stored for generating 1064 nm radiation. However, this still leaves $E_{out} = 4.2$ mJ of unused 809 nm light returning to the diode arrays with each pulse. Not only is this wasteful, but it will likely have negative implications on the laser diode lifetimes over long term operation. In order to apply this leftover pump energy for 1064 nm laser action, we send it back into the slab for another 2-passes with the 4PPC. For these estimates, we need to add the passive losses of the 4PPC and increase the number of passes from 2 to 4 in our calculations. This optic reduces our stored energy after only 2 passes, but a net increase is realized with 4 passes. We were able to measure the 4PPC prototype's transmission loss at 9% ($\eta_{4PPC} = 0.91$) for the p-polarized diode array light. We selected a 4PPC loss of ~ 4% ($\eta'_{4PPC} = 0.96$) for s-polarized light as the post 2-pass pump energy is reconfigured for absorption passes #3 and #4. This loss proved to be too difficult to measure without a small 809 nm diode test source, so we were forced to derive a loss estimate from manufacturer specifications regarding polarization beam splitter performance and the p-polarization test. To find the total stored energy in the Nd:YAG slab, which includes the first 2 passes as well as the 2nd pair of pump passes, we use

$$E_{st(4P)} = \eta_{PC}\eta_{CE}\eta_{FI}\eta_{abs}\eta_{QE} \cdot (\eta_{4P}E_{LD} + \eta_{PC}\eta'_{4PPC}E_{out}) \qquad (2)$$

and get a result of $E_{st(4P)} = 8.0$ mJ, an increase of 0.8 mJ (11.1%) from the 2-pass pumped case. Even with our relatively lossy 4PPC, and accounting for the passive losses for the p and s-polarization cases, we use

$$\eta_{abs(4P)} = 1 - \{(\eta_{abs(2P)} \cdot E'_{LD} + [E_{LD}(1 - \eta_{4PPC} \cdot \eta_{PC}) + Eout \cdot (1 - \eta_{PC} \cdot \eta'_{4PPC})]\} \cdot 1/E_{LD} \qquad (3)$$

to find a 4-pass true absorption efficiency, accounting for passive losses, of $\eta_{abs(4P)} = 0.88$. If we could use perfect, lossless optics in the pumping system, Equations 1 and 3 says the absorption efficiency would be $\eta_{abs(4P)} = 0.98$. To help recoup some of this scattered energy in the 4PPC, our custom optic manufacturer assures us that the next generation unit can be improved to approximately 6% and 2%, or 0.94 and 0.98 for η_{4PPC} and η'_{4PPC}, respectively. If achievable, then we should produce stored energies for lasing in our 1.5 mm thick slab of $E_{st(4P)} = 8.3$ mJ; a 15.3% improvement over 2-pass pumping, and a 4-pass absorption efficiency of $\eta_{abs(4P)} = 0.91$.

Taking scattering and passive loss reduction one step further, we have plans for new s-polarized, lensed diode arrays. The next generation 4PPC will be configured such that the first pass through the optic will reflect off the internal polarizer and out the $\lambda/4$ plate toward the slab. This allows us to delay the unavoidable 5% p-polarization transmission loss associated with right angle polarization optics until after the first 2 pump passes. If we assign values of 0.98 and 0.93 for η_{4PPC} and η'_{4PPC}, respectively, our stored energy would be $E_{ST(4P)} = 8.5$ mJ and the 4-pass absorption efficiency would achieve $\eta_{abs(4P)} = 0.94$.

Estimating the pumped volume is critical to accurately modeling the laser performance. The width and depth of the inversion density is determined by the slab thickness and the diode array width, respectively. When a stack of diode arrays are unlensed, or somewhat confined with a macro cylinder lens, we have found the best method to calculate the pumped volume is to carefully model the setup with non-sequential ray tracing software in combination with an experimental CCD imaging study while the laser head is actively being pumped, but using no active cavity feedback, using the Nd:YAG's 1064 nm fluorescence if possible.[4] Even after all this effort, the effective inversion density has to be estimated numerically and often tweaked to match the laser's performance. However, if the individual diode bars are collimated as our arrays are, then the pump beam can be precisely imaged, measured, and a constant $1/e^2$ beam thickness assumed throughout the absorption process. We measured a $1/e^2$ Gaussian beam thickness of 0.08 cm, or a "waist" of ω_{pump} = 0.04 cm, with a CCD laser imaging data system.[10] Our pumped volume used was $V_{pump} = 2xy\omega_{pump}$, where x and y are the slab thickness (0.15 cm) and the pump beam width (2.2 cm), respectively. With and without our relatively lossy 4PPC and a pumped volume of V_{pump} = 0.26 cm^3, we estimate peak inversion densities of $N1_{2P}$ = 1.45 x 10^{18} cm^3 and $N1_{4P}$ = 1.63 x 10^{18} cm^3 in the 2-pass and 4-pass cases, respectively. Using these estimates of the inversion density as well as the mode field diameters in the zigzag and non-zigzag axes, we can now utilize a previously described Q-switched laser model to predict oscillator performance for both pumping cases.[11,12] For measured Gaussian mode diameters of 0.8 mm and 1.0 mm in the zigzag and non-zigzag dimensions, respectively, we predict the laser will produce 3.9 mJ, 6.5 ns pulses in 2-pass pump mode, and 4.3 mJ, 6.0 ns pulses when 4-pass pumped. The laboratory performance characteristics of the laser in both pumping modes are shown in Table 1.

As expected, the increase in inversion density using the 4-pass technique leads to a substantially higher Q-switched optical efficiency. Even accounting for the ~15% loss introduced by the fast axis collimating lenses on the diode arrays, the 4-pass pumped laser runs nearly 20% optically efficient, with an improvement in output energy of 33% over the 2-pass case. With higher quality coatings on the 4PPC optics, a reconfigured polarization path, and new diode arrays, we expect the improvement differential to increase even further.

The relative sensitivities of laser operation in 2- and 4-pass configuration to diode temperature were also investigated. Since diode array wavelength shifts nominally by ~0.25 nm/°C, tight temperature control over the pump source is often required to keep the oscillator output power maximized; this patently adds unwanted complexity and additional power consumption to the system.

It was believed that the longer effective pump length of 4-pass pumping might assuage the diode temperature problem somewhat. We assessed the dependence of both pump modes on diode array temperature experimentally. With the pump arrays operating at a fixed power and duty cycle, a portion of the photoluminescence (PL), or spontaneous emission, emitted from the slab was captured and semi-collimated by a lens, directed through a pair of 1064 nm interference filters, and imaged onto a power meter. The 1064 nm PL intensity was recorded every 0.5 °C over the range 14.0 °C - 34.5 °C for both the 2-pass and 4-pass pumping cases. The results of the temperature sweep are shown in Figure 3.

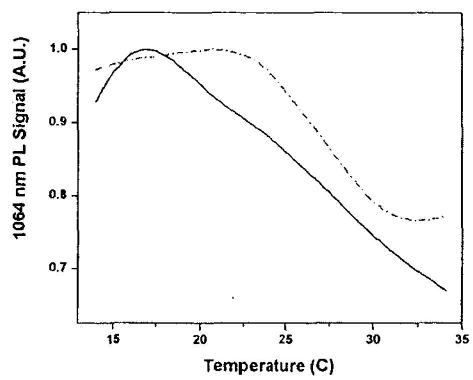


Fig. 3. 1064 nm PL vs. diode temperature in 2-passed (solid) and 4-passed (dashed) pump mode. The 2-pass pumped configuration produces a peak inversion around 17°C while the 4-pass method is broader in ΔT and peaks around 21°C.

The peak of the each PL curve shown in Figure 3 has been normalized to 1.0 for comparison. It is clear from the plot that the PL signal is significantly less temperature sensitive when 4-passed, remaining within 3% of the peak from 14-24 °C, whereas when 2-passed the range closes to 15-19 °C. From this data, it stands to reason that a laser system utilizing 4-pass pumping would only require fairly loose control over array temperature in order to maximize output power, and in fact, allow the lase to operate at a higher temperature.

Conclusion:

A simple and compact pumping scheme based on polarization control was developed to enhance optical efficiency in small slab lasers used for space-based lidar missions. The scheme produced 4 passes of pump energy through the same volume of gain medium, increasing the optical efficiency by ~33% over the conventional 2-passed case. Improvement of the 4PPC optic quality and new diode arrays should enhance performance to an even greater advantage. It was also found that the 4-pass pumping method significantly decreased the dependence of laser output power on diode temperature, thereby decreasing the thermal control requirements for space operation.

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Table 1. Summary of Test Cavity Performance with 2-Pass and 4-Pass Pumping

Pump Passes	Pulse Energy (mJ)	Pulse Width (ns)	Optical Efficiency
2-Pass	3.3	7.0	14.6%
4-Pass	4.4	6.5	19.5%