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IMPROVED SOLID-STATE LASER SOURCES

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Final Technical Report for the period
2 June 1981 - 1 June 1982

August 1982

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IMPROVED SOLID-STATE LASER SOURCES

Final Technical Report

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Principal Investigator

Robert L. Byer

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IMPROVED SOLID-STATE LASER SOURCES

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ABSTRACT

During the first program year we have demonstrated diffraction limited output of 600 mJ from an unstable resonator Nd:Glass slab geometry oscillator. We have investigated, in detail, slab geometry lasers and have verified by careful experiments all important predictions of the slab theory. To date we have generated 10 J of output energy at 2.5 Hz from a single multimode, non-Q-switched, slab oscillator at 3.5% storage efficiency, 2% slope efficiency and 1.6% extraction efficiency. We have doubled and Raman shifted the Q-switched 600 mJ slab glass oscillator.

We have extended the slab concept to Nd:YAG. Preliminary measurements show that the slab geometry eliminates thermal focusing and stress induced birefringence in Nd:YAG.

We have demonstrated the advantages of the miniature pedestal growth technology by growing $\text{Eu:Y}_2\text{O}_3$ single crystal fibers in addition to Nd:YAG and sapphire single crystal fibers.

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IMPROVED SOLID STATE LASER SOURCES

Robert L. Byer

I. INTRODUCTION

A. Progress in Slab Geometry Laser Sources

The goal of this program is to research slab geometry solid state laser sources to improve their performance capabilities for laser fusion applications. Specifically, our Stanford Test Bed Slab Glass Laser System was designed to provide experimental verification of the slab model computer program and to demonstrate operation at the modest output energy of 600 mJ from the oscillator, 1.2 J from the pre-amplifier and 6 J from the final amplifier at 5 Hz repetition rate. An overall wall plug efficiency of 1% was projected at operational lifetimes of greater than 10^7 pulses.

The slab glass effort has achieved the goals of verifying the slab laser performance limitations projected by an extensive computer model program. Based on measurements of focusing, birefringence, fracture stress, pumping efficiency, gain oscillator performance and laser beam quality, we have verified our computer model of slab geometry lasers. We can with confidence design slab geometry laser systems. A second, and significantly improved slab laser system is now being constructed based on our one year measurement effort.

The need for high energy, efficient laser sources for laser fusion applications is well recognized.¹ This program addresses problems of laser geometry, flashlamp pumping of glass and crystalline laser host materials, and thermal cooling approaches required for improved performance of high pulse energy laser systems.

The progress in slab glass laser research is reviewed in Section II. We are now confident that a laboratory scale 10 J, 10 Hz slab geometry oscillator/amplifier system can be built based on our current designs. We project wall plug efficiencies of the slab glass source to be greater than 1% and potentially as high as 2%. Diffraction limited spatial mode output has been demonstrated thus permitting efficient frequency extension via nonlinear conversion processes.

B. Progress in Crystalline Slab Geometry Laser Sources

The use of crystalline laser host materials offers the potential advantages compared to glass of higher thermal conductivity and greater mechanical strength. Together these attributes give crystalline, as opposed to glass lasers, an order of magnitude higher average power capability. However, the apparent advantage of crystalline materials is restricted by flashlamp limitations. Thus unless crystalline walled flashlamps can be engineered the potential offered by crystalline host materials cannot be fully realized.

II. SLAB GLASS AND SLAB CRYSTALLINE LASER RESEARCH

A. Slab Glass Progress During the Past Year

We have made rapid progress during the past year in our understanding and implementation of the slab glass laser source. However, it should be recognized that this progress comes after nearly three years of preliminary and often frustrating research on the slab laser approach. It should also be mentioned, as indicated in the original proposal, that laser research is expensive and that the slab laser research effort is supported in part by

the Army Research Office, by the Livermore National Laboratory and by N.A.S.A.

This program is unique in that it combines the improved solid state laser devices with their application to measurements. The long range goal, and the reason for our slab geometry study effort, is to provide laser sources for applications that include laser spectroscopy studies, and X-ray generation via laser driven plasmas.

Our principal effort during the past year was the completion of the slab computer model program and its verification by extensive measurements using our test bed slab glass laser source. Laser performance measurements were secondary and are only now being pursued.

The computer model is described in more detail in Appendix I. It allows the calculation and display of the thermal field, the stress field, and stress induced birefringence, the surface stresses, surface curvature induced by stress, zig-zag path propagation in the slab and slab performance under a variety of thermal and stress boundary conditions.

The Stanford test bed slab laser system was used to measure the slab performance and to verify the model predictions. We have verified the projected focusing and beam distortion effects, the birefringence averaging due to the zig-zag optical path and the expected depolarization under fully pumped conditions.² These results are described in Appendix II which is an abstract of the paper was presented at the C.L.E.O. Conference in April 1982.

We have also determined that coolant effects and Brewster angle window effects are important. We have found ways to eliminate potential beam distortion due to these effects. We have verified the storage efficiency,

the slope efficiency and the extraction efficiency of the slab configuration laser source. The 3.75% storage efficiency, 2% slope efficiency and 1.65% extraction efficiency averaged over the entire slab volume are impressive performance levels. We expect to improve these efficiencies by a better reflector structure design, use of higher doped phosphate glass, and by optimum flashlamp design.

Recently we have operated the slab laser in an unstable resonator³ and radial birefringent resonator⁴ configuration. The 15 cm long slab is a factor of two shorter than optimum and thus has not permitted us to achieve the best oscillator output. However, we have demonstrated 600 mJ output in a 5.5 mm diameter unstable resonator mode under Q-switched operation. The energy fluence in the resonator is 4 J/cm^2 which is twice that normally supported by Nd:YAG oscillator sources. The short slab and lack of gain forced operation at 2.5 Hz repetition rate under these resonator conditions.

During the past year we attacked a number of technical issues which were important in the quest for improved performance and efficiency of the slab geometry Nd:Glass laser source. These technical details are summarized in this section for future reference.

We developed a very highly reflective evaporated silver layer on the back of pyrex glass. The silver layer is protected from flashlamp evaporation and attack by the coolant by an evaporated copper layer 1 μm thick followed by an electro-deposited nickel layer a few mills thick. The resultant reflector is cheap, efficient, free from attack and highly reflective. We have tested the reflector in Nd:YAG laser sources and plan to use it in the

next generation Nd:Glass laser system in place of the present silver on nickel plated aluminum reflector.

We pursued uv reflectance coatings on flashlamps and on the tube surrounding the flashlamps. The directly coated flashlamps suffered coating damage quite early. The efficiency of the Nd:YAG laser test source decreased with the coating on the lamp. The dielectric coated tube, provided by C.V.I. did not enhance the Nd:YAG efficiency. Our conclusion is that favorable results are not easily obtained by special coatings on, or around, the lamp.

We operated flashlamp pumped Nd:Glass slabs with 1.5 μ sec long pulses. The ultraviolet shift led to very poor laser performance. In fact, the glass was more efficiently pumped by the 2-10 μ sec long afterglow than by the main pulse. Experiments with 150 μ sec to 200 μ sec lamp pulses showed that optimum laser performance is achieved at less than 2500 A/cm² current density.

We investigated MgF₂ coatings on phosphate glass to protect the glass from the water coolant. The coatings survived long flashlamp pulse pumping but rapidly degraded for microsecond pulse pumping due to excessive uv emission. Our conclusion is that coatings should be avoided.

We operated the LHG-8 and LHG-5 Nd:Glass slab laser sources. LHG-5 is a more appropriate glass due to its mechanical properties and its near zero dn/dT. We are conducting tests of 8% doped LHG-5 glass and other highly doped glass compositions to measure the overall laser efficiency.

We investigated, in detail, end and coolant effects on slab glass laser beam quality. We have learned to eliminate the end effects and thus improve focusing and beam quality.. Uniform coolant flow eliminated beam distortions due to uneven coolant flow over the glass surfaces. Our conclusion is that liquid coolant must be avoided if long term, contamination free,

operation is to be achieved. We propose to use gas cooling in the next version slab geometry glass laser system.

We have operated at 4 J/cm^2 fluence with a 20 nsec pulse in a Q-switched unstable resonator oscillator without coating or Q-switch damage. The optimum fluence level for LHG-5 glass, at two time threshold, is 8 J/cm^2 . We expect to achieve operation at this level in the amplifier stage.

Fabrication of the slab glass pieces is now commercially feasible at a number of optical facilities. We expect fabrication costs to decrease as the technical community becomes familiar with the properties of the phosphate glass.

A longer slab, or lower magnification resonator, or thinner slab, as is being prepared for the next generation slab laser source, should allow operation at the projected 10 Hz repetition rate.

At present a 15 cm long slab stores greater than 10 J of energy. We expect to extract over 50% of the stored energy in a double pass final amplifier configuration and thus achieve the projected 6 J of output energy. Future, optimized designs, should yield 10 J at 10 Hz for 100 W of average output power from the slab glass source.

We are working closely with the U.S. Army, N.A.S.A. and private corporations such as R.C.A., McDonnell Douglas and General Electric in our glass slab research effort. We plan to continue to transfer our knowledge in slab geometry lasers as our research effort progresses.

We have theoretically investigated potential crystalline slab laser systems. The primary requirements were efficient operation, and the availability of large, high quality crystals. Very few of the currently known laser crystals meet these requirements. At this time MgF_2 , and SrF_2 are potential crystalline

hosts as is sapphire and perhaps YLF. We believe that GGG is a candidate but color center formation and iridium inclusions during growth must be eliminated. YAG is not available in large sizes.

We have also eliminated Ni^{++} and Co^{++} doped MgF_2 from consideration because of the low gain cross-section and resultant very high saturation fluence. Our design criteria demands adequate oscillator gain to support an unstable resonator oscillator and low enough saturation fluence to avoid damage at twice the Q-switch threshold where the circulating fluence is twice the saturation fluence.

The $4 \times 10^{-20} \text{ cm}^2$ cross-section of the phosphate glasses with the resultant $E_{\text{sat}} = 4 \text{ J/cm}^2$ is nearly ideal for unstable oscillator design. The gain is also adequate to support power amplifiers that operate at $2 E_{\text{sat}}$ for efficient energy extraction.

Both N^{++} and CO^{++} doped MgF_2 are too low gain to be efficiently used. Nd:YAG has too large of a gain and too small E_{sat} to be effective in large volumes for energy storage and extraction.

Interestingly, the Ruby laser, at temperatures just below room temperature, has a nearly ideal gain cross-section, E_{sat} and crystalline host material. It remains to be seen if the chromium pump band absorption efficiency is high enough to overcome the 50% efficiency penalty of the three level laser system. Preliminary measurements show that Ruby operates at 0.3% overall efficiency due to the high threshold energy penalty of the three level system.

B. Slab Nd:YAG Progress During the Past Year

In our proposal we considered the improved performance that might be achieved by the application of the slab concept to crystalline laser materials.

We investigated, on a theoretical basis, various laser host crystals and found that, on average, crystalline slab lasers offer an order of magnitude better average power output than glass based slab lasers. However, glass is available in large, high quality pieces while most crystalline hosts are not.

We chose to investigate slab geometry performance in Nd:YAG because of its availability and its well characterized laser parameters. We proceeded to fabricate three YAG slabs from 3/8" diameter rods that were on hand. We pumped the YAG slabs with a borrowed cw lamp commercial laser system* at up to 4 kW of input power. Using 50 mm long x 4 mm x 8 mm slabs we have generated 30 W of output power and have verified that the slab geometry eliminates birefringence in Nd:YAG and, over 2/3 of the slab volume, eliminates thermal and stress induced focusing. These very promising results were presented at the C.L.E.O. Conference. (See Appendix III).

Recently we have considered Ruby as a potential slab laser material. The advantages of Ruby include excellent flashlamp absorption bands and thus reasonable pumping efficiency, an excellent thermal and mechanical host crystal that is available in large sizes, a temperature dependent gain cross-section (two orders of magnitude variation from 77°K to 273°K) and intrinsic absorption at the .6943 μ m pump wavelength for potential superfluorescence isolation. We propose to experimentally investigate Ruby in our slab test bed laser system.

In the future other crystalline host materials can also be tested in the slab test bed system. The next generation design will allow separate slab temperature control so that measurements can be made from cryogenic to above room temperature. We plan to investigate second harmonic generation using

* on loan from Livermore National Laboratory.

both cw and acousto-optic Q-switched Nd:YAG slab laser sources, with warm phasematching LiNbO_3 crystals previously grown at Stanford.⁶

Design projections show that slab YAG is capable of operation at more than an order of magnitude higher average power in an unstable resonator configuration than currently available 30 Hz commercial laser sources.

Crystal size limitations and the onset of super fluorescence limit output of Nd:YAG to near 1 J per pulse. However, repetition rate is set only by flashlamp limitations in the slab geometry and not by thermal focusing or stress induced birefringence as is the case for the present rod geometry laser sources.

We intend to demonstrate the scaling capabilities of slab YAG and to pursue a study of high average power SHG of the near diffraction limited source.

III. SUMMARY OF RESEARCH PROGRESS

In this section the program objectives originally proposed are reviewed, modified and extended. The accomplishments projected for 1981/82 are compared with actual research results.

The program objectives were as follows:⁷

- To investigate the slab geometry approach to solid state laser sources by a combined theoretical and experimental program,

- to apply the latest laser technology to slab geometry Nd:Glass laser design and testing,

- to investigate new crystalline laser materials,

- to apply the slab geometry to crystalline laser systems,

to investigate nonlinear frequency conversion techniques including Raman and nonlinear conversion processes in crystals.

During the past year we have demonstrated a slab glass oscillator in 3% doped LHC-5 glass and have operated the system for a nine month period. We delayed Raman shifting and amplifier studies to concentrate on slab geometry effects and on verification of the slab model. This work was completed in February 1982 as part of John Eggleston's Ph.D. thesis.

We tested the first slab Nd:YAG laser in December 1981. We have made extensive measurements since then that have verified the expected performance improvements in slab YAG.

We have demonstrated SHG of the 600 mJ slab glass oscillator with up to 20% efficiency. We are limited by available optics from boosting the SHG efficiency to the 40% conversion efficiency level. We have, in March, generated stimulated Raman scattering from both the second harmonic and fundamental pump wavelengths. We took delivery of the fabricated high doped LHC phosphate glass in July and we are conducting efficiency comparison tests.

During the next program year we propose to discontinue the studies of $\text{Co}^{++}:\text{MgF}_2$ and $\text{V}^{++}:\text{MgF}_2$. Recent numerical calculations have shown that these laser hosts offer too little gain to be useful in Q-switched oscillator or amplifier high pulse energy laser systems. In place of new laser host studies, we propose to initiate studies of gadolinium scandium gallium garnet as a potential high pulse energy oscillator/amplifier system for fusion study applications.

Our current plans call for completion of an 10 J, 10 Hz oscillator/amplifier slab glass laser system by December 1982. We then plan to study oscillator and amplifier performance, energy efficiency and gaseous conduction

We also plan to use the laser source at both the fundamental and second harmonic wavelengths for X-ray generation.

We also propose to complete our studies of the slab Nd:YAG source during the next program year. We plan to use the high average power source to study average power limitations of SHG.

Our slab computer model program allows us to design high pulse energy laser sources with good confidence of their projected performance. We can indeed proceed to design and demonstrate a 1 Hz, 100 J Nd:Glass slab laser system. We consider the 100 J slab glass laser system a potential design option that should be pursued because of its application to X-ray generation.

This year we have accomplished all of the major goals set forth in the program objectives. We hope to make similar progress in the second year of this program.

IV.

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APPENDIX I

SLAB DISPLAY

During the past two years we have developed a set of programs to calculate and display important slab laser parameters. The program considers the slab temperature distribution and from temperature profiles proceeds to calculate the stresses. The induced stresses are calculated on the reflecting face and on the non-reflecting face near the edges.

The stress field can be displayed such that tension and compression are distinguished and the local vector direction displayed. From the stress field as input, a separate program traces rays through the slab along the zig-zag path and calculates depolarization and focusing. Stress induced surface deformations are also calculated and displayed.

The programs were written so that rod geometry could be treated as a special case. The rod geometry stress problem can be solved analytically thus giving a check on the numerical solution. The slab stress program was carefully checked against measurements made using the Stanford test-bed slab glass laser. Measurements of energy storage efficiency provided the calibration of the heat generated in the slab as a function of flashlamp energy. This was the only scale factor that needed to be determined experimentally.

Recent measurements of depolarization, residual focusing and end effects have verified the predictions of the slab display program. The program is now useful as a design tool for slab geometry laser sources.

The slab geometry assumed by the slab display program is shown in Fig. A-1. The length of the slab lies along the z axis. The reflecting

Definition of Slab Dimensions

FIG. A-1--Slab geometry assumed for slab display programs.

faces and, therefore, the pumping faces are y faces. The x faces are assumed to be thermally insulated. We take the slab to be approximately 3:1 in the $x:y$ dimensions. Uniform pumping is assumed over the entire y face. The input and exit faces are near Brewster angle but cut so that the interior ray is totally internally reflected from the y face. The lower index of refraction for glass than for Nd:YAG make the internal reflection angle lie nearly critical angle for water or ethylene glycol coolant. The surface must remain clean and the coolant fluid non-absorbing to minimize the reflectance loss at the internal reflection face.

The menu of displays available from the slab display program is shown in Fig. A-2. We proceed to present the display options in the order listed in Fig. A-2 even though the order is not logical from a design viewpoint. Each display is briefly discussed in turn and important features pointed out.

The slab display program is written in Pascal and run on a PDP11/44 minicomputer. The display is formed on an AED color monitor. The hard copy shown here is a grey coded reproduction of the AED color display. It is reproduced on a Versatec high speed line printer with the graphics output option.

Figure A-3 shows the stresses in a pumped slab. The circle denotes the center of the slab. The vertical and horizontal directions are the y and x axis, respectively. Thus only $\frac{1}{2}$ of the slab is shown. The rest of the slab is symmetric about the y and x axis. The color monitor presents compression as green and tension as blue. The grey coded reproduction shows light and dark grey

The plot of tension/compression in the slab shows that the center region is under compression as expected. The edges are in tension. The cross-over region from compression to tension introduces optical birefringence that is illustrated in a following figure.

AED 512B.V91

>HEL SLAB/HOYAGL

RSX-11M BL26 MULTI-USER SYSTEM

GOOD MORNING

20-JAN-82 09:19 LOGGED ON TERMINAL TT3:

>RUN SLABDISP

What is the master file?

OURHENE

OURHENE is the master file.

Choose one of the following options by letter:

- A: Stress Display
- B: Contour of Heat
- C: Contour of Temperature
- D: Contour of Depolarization
- E: Contour of Phase Difference
- F: Six Plots of Heat
- G: Six Plots of Temperature
- H: Six Plots of Depolarization
- I: Six Plots of Phase Difference
- J: Bulge of Reflecting Face
- K: Stress on Reflecting Face
- L: Stress on Non-Reflecting Face
- M: Focal Power of Slab, X direction.
- Z: End Slab Display Program

Enter Option, then be ready to wait a bit while files are read:

D

SHOULD NEXT PLOT BE ON AED OR PEN PLOTTER? A/P: A

FIG. A-2--The menu of display options for slab display program.

A

STRESSES IN PUMPED SLAB

THICKNESS 0.600 WIDTH 2.600
 CIRCLES ARE PLACED EQUAL TO INSTANTANEOUS DEFORMATION;
 BETWEEN POINTS IS 100,000 STRESS UNITS.
 CIRCLE IS AT SLAB CENTER.
 COMPRESSION TENSION

FIG. A-3--Stresses in the pumped slab. The circle is the slab center. Only $\frac{1}{4}$ of the slab is shown.

The tension on the slab surface leads to the possibility of slab breaking at a stress concentration point along the surface. The breakage stress in the z-direction is shown in a later figure.

Figures A-4a and 4b show the surface stress in the reflecting and x-face of the slab. The surface stress, as mentioned above, eventually exceeds the fracture stress limit of the material and leads to fracture of the slab. The stress in the x direction on the y reflecting face is greatest at the slab center. It decreases to zero at the x face as required by the stress boundary condition.

The stress in the z direction on the y face actually increases near the x,y corner. This is the location of the maximum surface stress and the place where slab fracture initially occurs. Experiments with two slabs have verified that cracking occurs at the x-face due to stresses in the z direction. This suggests that rounding of the edge may reduce the z-direction surface tension in the corner.

The bulge in the y face has important consequences on the beam residual focusing. The bulge is shown in Fig. A-5 for the y face from the center to the x-edge of the slab. The stress induced y face bulge leads to residual focusing effects for which the zig-zag path does not correct.

The focusing of the zig-zag ray is shown in Fig. A-6. The focal power in diopters (inverse meters) is negligible over most of the slab. However, the focal power turns negative and becomes significant for the final 13% of the slab along the x direction. Therefore, 87% of the slab area can be used in laser operation. Attempts to eliminate the residual edge defocusing

SURFACE STRESS: REFLECTING FACE. CYAN=SZZ, MAGENTA=SXX

FIG. A-4—Surface stress along the y face from the center to the edge of the slab. The z-direction tensile stress is maximum in the y,x corner. Experiments have shown that the slab fractures initiate in this region.

FIG. A-5--Bulge in the y or reflecting face vs distance along the x axis. This bulge is due to thermal induced stresses in the slab.

FOCAL POWER OF SLAB AS FUNCTION OF POSITION, X DIRECTION

FIG. A-6—Focal power of the pumped slab in diopters due to bulge in the y face. The focal power remains insignificant over 87% of the y face. High optical quality spatial beam output does not permit energy extraction from the final 13% of the slab near the x face.

have not been successful. Thus excess material is required to make the transition to the x-face and extraction efficiency of stored optical energy is reduced.

Experimental measurements of the test-bed Stanford slab glass laser have verified these focal length predictions.

The stresses induced in the slab are a direct consequence of temperature gradients induced in the slab by optical pumping of the volume and surface cooling. The slab display program also calculates the temperature profiles in the slab based on uniform or non-uniform pumping or cooling.

Figure A-7 shows a grey-coded plot of temperature in the slab. Again, the circle in the slab center and only one-fourth of the slab is shown. In this plot the slab is 13.26°C warmer in the center than at the edges. The temperature induced stress reaches the fracture limit for a temperature difference of 300°C.

Figure A-8 shows temperature profiles of the slab that is illustrated in Fig. A-7. The axis of the plots are temperature vs x-direction. The parameter is the distance from the slab center toward the y face which lies at $y = 6/6$. Again, these temperature profiles are used in the stress calculations which have been shown above.

The slab geometry leads to a depolarization that is primarily x-y oriented. An infinite slab would have stress induced birefringence components only along the x and y directions. Thus, for light polarized along these principle axis, the infinite slab would not show any stress induced birefringence

TEMPERATURE

WIDTH=2.850 THICK=0.860
CIRCLE AT SLAB CENTER. ONE COLOR CHANGE= 1.734850E+00

1.734850E+00

-1.326234E+01 AVG = -2.070020E-06 9.290714E+00

Fig. A-7--Temperature profile in the slab assuming uniform volume pumping and surface cooling.
Only $\frac{1}{4}$ of the slab is shown.

FIG. A-6--Temperature profiles vs x direction for various locations in the slab from the center at $y = 0$ to the y face at $y = 6$.

In practice, the slab is finite in the x dimension. Thus we expect some depolarization near the x -face. The depolarization that is evident for a 632.8 nm helium neon probe beam is shown in Fig. A-9. Again, only $\frac{1}{2}$ of the slab is shown. The light area is zero depolarization. Each step in grey corresponds to 7% depolarization in the 15 cm long pumped glass slab. The maximum depolarization for this case is 30%.

The calculated depolarization is plotted in Fig. A-10. Here the magnitude of the depolarization is plotted vs the x -direction for various positions along the y axis from the center to the y face. The near cyclic depolarization near the x face is due to the rapid change in stress magnitude and direction. Experiments performed using a helium-neon probe laser on a pumped glass slab have verified the theoretically predicted depolarization magnitude and spatial modulation features. The depolarization at 1.05 μm is expected to be less than at 0.6328 μm by the wavelength ratio. In any case, the average depolarization over the entire slab is only 2%. Measurements have verified that the slab geometry does indeed lead to polarized laser output.

In summary, we have shown in this Appendix the useful displays generated by the program Slab Display. The calculation capability of Slab Display include the ability of changing thermal boundary conditions, slab dimensions, slab material parameters and surface stress conditions. The program has been compared to detailed measurements using the Stanford test-bed slab glass laser system. The agreement between theoretically predicted results and experimentally measured parameters is excellent. The program can, therefore, be used as a design aid with confidence in the predicted results.

DEPOLARIZATION

WIDTH=2.850 THICK=0.860

CIRCLE AT SLAB CENTER. ONE COLOR CHANGE= 7.692308E-02

0.000000E+00

AVG = 2.346405E-02

1.000000E+00

FIG. A-9--Depolarization at 632.8 nm probe wavelength over $\frac{1}{4}$ of the slab for a zig-zag beam path. The maximum depolarization is 30.1%.

FIG. A-10--Plots of depolarization at 632.8 nm probe wavelength vs x-axis direction for various y positions from the center to the y faces.

APPENDIX II

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SLAB GEOMETRY SOLID STATE LASERS

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ABSTRACT

Using a slab geometry significantly reduces thermal focusing, stress induced biaxial focusing, and birefringence in a solid state laser host. Theoretical and experimental verification of this reduction is presented along with performance data for two phosphate glass slab laser systems.

SLAB GEOMETRY SOLID STATE LASERS

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Solid state lasers have been traditionally fabricated in the form of a pencil-like rod. Under thermal loading, these host rods manifest optical distortions which include thermal focusing, stress induced birefringence and stress induced biaxial focusing.¹ These effects can severely degrade the optical quality of the laser output at medium pump powers, and completely extinguish laser action at high pump powers. Clearly the elimination or reduction of these undesirable optical effects is essential to the development of high average power solid state laser systems.

In this paper we present the results of theoretical and experimental work on two laser systems employing a laser host in a 'zig-zag' slab geometry.²

The first system, located at Stanford University, is a slab laser test-bed which has been designed to experimentally confirm the slab geometry laser theory. The performance goal of the Stanford test-bed slab glass laser in an amplifier/oscillator configuration is 6J per pulse at 10 pps or 60W of average power.

The second system, located at the Swiss Nuclear Research Institute, Villigen, Switzerland, is designed to operate at 10J per pulse, 50 Hz repetition rate or 500 W of average power. This laser is to be Raman shifted in hydrogen and HD to provide tunable output near 6.0 μm for precision Lamb shift measurements in muonic hydrogen atoms.

The slab geometry shown in Fig. 1 is chosen to orient the stress birefringence in a single direction so that a linearly polarized laser beam can be aligned along the birefringence axis and thus suffer no depolarization.

The zig-zag optical path averages out the thermal and stress focusing such that to first order these focusing effects are eliminated.

The theoretical work is based on a set of computer programs that include a general thermal and mechanical model for a slab, which in turn generates the input for a polarization sensitive ray tracing program to determine residual focusing and birefringence effects. Theoretical predictions, including scaling laws and system limitations will be presented.

The experimental results include a detailed comparison between experiment and theory. As an example, the computer generated results and the experimental measurements for birefringence are shown in Fig. 2 through a 15 cm slab glass system. The experimental results include performance figures for a neodymium doped phosphate glass laser system. This system, in an unoptimized configuration, has produced over 18 watts of average output power at 1.06 μm . Measurements show that under these strong thermal loading conditions the zig-zag slab is diffraction limited for a 4 mm diameter probe helium neon beam. This performance is an order of magnitude better than the output achievable in a rod glass system. The results of Q-switching and amplification experiments will also be presented.

The performance and recent progress of the Stanford and Swiss Institute of Nuclear Research slab geometry glass laser systems will be discussed.

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Fig. 1--Top view of a slab laser showing the optical path and the position of the flashlamps.
Front view of a slab laser showing the front face of the slab, flashlamp positions and the reflector structure.

FIG. 2--Depolarization vs position for a scan along the X-axis (see Fig. 1), starting at the center of the front face and moving down to the slab edge. Resolution is limited by the size of the probe beam.

APPENDIX III

POLARIZED cw Nd:YAG LASER USING A SLAB GEOMETRY

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ABSTRACT

We have demonstrated a Nd:YAG laser using a zig-zag slab geometry. It is theoretically possible to build a polarized 100 Watt slab laser using low optical quality YAG.

This paper would not be appropriate for the poster session.

POLARIZED cw Nd:YAG LASER USING A SLAB GEOMETRY

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When a solid state laser is pumped hard, temperature differences within the laser material create stresses. These stresses, along with the residual stress remaining from crystal growth, make it difficult to efficiently extract polarized output from high power Nd:YAG lasers using the traditional rod geometry. We have demonstrated that both thermal and residual birefringence can be eliminated by using a geometry in which the laser beam zig-zags through the laser material. Our observations and calculations indicate that it is possible to build an efficient 100 Watt Nd:YAG laser with polarized output and that it is not necessary to use stress-free Nd:YAG material.

There are two reasons for the greatly reduced birefringence in a zig-zag slab. It has long been recognized that in the center of a rectangular slab, the stresses are parallel with the slab face, and thus light polarized either parallel or perpendicular to the slab face passes through the center of the slab without depolarization.¹ The second reason, a generally unrecognized advantage of the zig-zag slab, has to do with the zig-zag rather than with the rectangular shape. A careful look at the alignment of the stresses within a slab shows that, to first order in the fractional depolarization, propagation through the top half of the slab cancels the depolarization caused by propagation through the

bottom half as shown in Fig. 1. Thus if the depolarization through any one segment of the zig-zag path is much less than one, the zig-zag path through the slab will be much less birefringent than the path straight through the slab.

Calculations using our computer model of light propagation through stressed slabs,² and observations of depolarization through stressed slabs with both straight-through and zig-zag paths, support these conclusions.

We present the results of experiments with a cw Nd:YAG slab laser, and calculate that a Nd:YAG zig-zag slab laser, with twelve bounces and dimensions of 4 mm x 6 mm x 100 mm, could produce 100 Watts of power in a single polarization. The slab would have a focal length of 1.6 meters, but since only one polarization is present, this is correctable. Thus diffraction limited output is possible.

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FIGURE CAPTION

Propagation through segment B cancels depolarization caused by segment A to the first order.

GEOMETRY OF ZIG-ZAG SLAB

FIGURE 1

APPENDIX IV

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SOLID STATE LASER SOURCES FOR REMOTE SENSING

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SOLID STATE LASER SOURCES FOR REMOTE SENSING

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ABSTRACT

Slab geometry solid state lasers potentially provide an order of magnitude improvement in performance over conventional rod geometry lasers. We review recent progress in slab Nd:Glass and Nd:YAG laser sources.

Single axial mode Nd:YAG may provide Doppler wind velocity measurements capability at 1.06 μm . Our measurements of a 3 msec long pulse, 10 Hz repetition rate single frequency Nd:YAG oscillator show a chirp rate of less than 30 kHz per microsecond.

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SOLID STATE LASER SOURCES FOR REMOTE SENSING

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I. INTRODUCTION

Remote sensing with laser sources has made tremendous strides during the past decade. The progress has been paced, however, by the slow development of the high power, narrow bandwidth, tunable laser sources required as transmitters for DIAL and coherent detection methods. Only recently, with the development of Nd:YAG pumped dye and parametric oscillator sources has near infrared and ultra-violet measurement systems been demonstrated.

This paper summarizes recent progress in solid state lasers that utilize the slab geometry with a zig-zag optical path as illustrated in Fig. 1.

Figure 1.

- a--Geometry showing axis of the slab.
- b--Schematic of the laser resonator with Brewster angle slab and zig-zag optical path.
- c--End view of the slab holder showing flashlamp position within the non-imaging flashlamp reflector structure.

The slab configuration solid state laser approach first proposed and investigated at General Electric¹ has been under development in our laboratory for the past three years. Slab geometry lasers offer a number of important advantages over the conventional rod geometry lasers. These advantages include the elimination of stress induced birefringence and thermal and stress induced focusing, and higher average output power limited only by stress induced fracture of the glass or crystalline laser host material. The progress in slab Nd:Glass and Nd:YAG lasers is discussed in Section II.

Coherent detection of wind velocity by Doppler velocimetry has now been established as a viable measurement approach at the CO₂ laser infrared wavelength range.² We have undertaken to design a single frequency Nd:YAG laser source for coherent wind velocity

measurements at 1.06 μ m. The Nd:YAG source offers the potential advantages

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compared to CO₂ based system of more than two orders of magnitude larger back-scatter coefficient, improved depth resolution, room temperature silicon diode based detection and a compact all solid state construction. The design and testing of a single frequency Nd:YAG oscillator is discussed in Section III.

II. SLAB GEOMETRY SOLID STATE LASERS

A. Introduction

Remote atmospheric measurements using the DIAL technique requires a high pulse energy tunable laser source. Only recently, with the development of the unstable resonator Nd:YAG source³ has 1 J pulse energies at 10 Hz repetition rate become available. However, the Nd:YAG pumped 1.4-4.0 μ m tunable parametric oscillator source⁴ has been limited to 10-50 mJ of output energy. The doubled Nd:YAG pumped dye tunable source has output pulse energies up to 100 mJ. For SO₂ measurements in the ultraviolet, the doubled dye laser output energy is typically 10 mJ.^{5,6} These energies are adequate for range resolved measurements over intermediate ranges, but are an order of magnitude below the requirements for space shuttle based LIDAR or DIAL measurements to 10 kilometer ranges. In addition, from a system viewpoint, the tunable OPO or dye laser is not as efficient or reliable as desired for long term measurement applications.

We began our slab geometry laser development effort three years ago in recognition of the need for a higher pulse energy, more reliable tunable source. Our approach was to tune the glass laser over its 200 cm⁻¹ wide bandwidth and to extend the tuning range by harmonic generation and by selective Raman shifting.⁷

Figure 2--Tuning range of Nd:Glass laser centered at 1.055 μ m followed by Raman shifting in gases. Harmonic generation in LiNbO₃ and KD*P can be used to extend the wavelength range into the visible and ultraviolet range.

Figure 2 illustrates the tuning range available with just a few Raman active gases. Harmonic generation can be used to extend the tuning range into the ultraviolet and visible spectral regions. The tunable Nd:Glass oscillator/amplifier source, followed by nonlinear frequency extension, combines the higher pulse energies generated in Nd:Glass with solid state reliability and system simplicity. The key to successful implementation lies in the application of the slab geometry concept.

To appreciate the advantages of the zig-zag slab geometry approach it is useful to compare the performance

limitations of rod geometry lasers to slab geometry lasers. To make the comparison

specific we consider the performance limits of a 15 cm long x 6 mm diameter Nd:Glass rod laser and a 15 cm long x 8 mm thick three-to-one aspect ratio slab Nd:Glass laser.

The performance limitations are summarized in Table I for LHG-8 phosphate glass. Phosphate glass was selected because of its high gain cross-section and negative dn/dT which helps to offset thermal and stress focusing in the rod laser.

TABLE I
Rod and Slab Geometry Laser Design Limitations

Rod geometry (6 mm dia. x 15 cm length LHG-8 phosphate glass)	Average flashlamp power. (Watts)	Effect
Birefringence	100	π phase shift
Thermal focusing	1000	-115 cm focal length
Stress focusing	1000	+70 cm focal length (biaxial)
Stress fracture	1000	Surface stress fracture limit
Slab geometry (8.3 mm x 25 mm x 15 cm length, LHG-8 phosphate glass)		
Birefringence	-	Eliminated by x,y,z geometry
Thermal & stress focusing	-	Eliminated by zig-zag optical path
Stress fracture	2000	Only design limitation

In the rod geometry, the stress fracture limit occurs at 5 Hz repetition rate at 200 J flashlamp energy or 1000 W of average input power. This stress fracture limit was verified experimentally by fracturing rods of Nd:Glass. Stress and thermal focal lengths are +70 cm and -115 cm at the stress fracture loading limit. These focusing effects must be compensated in the design of the laser oscillator to enable near diffraction limited performance. Since the stress and thermal focusing has both radial and tangential components, the focusing is not equivalent to a lens but is instead a biaxial focusing element that cannot be simply compensated by an additional lens.⁸

Finally, at 1/2 Hz repetition rate, or 100 W of flashlamp average power, stress induced birefringence is severe enough to cause a polarization induced phase shift of π radians. This in turn induces a severe loss for linearly polarized resonator designs that are required for Q-switching or frequency extension by nonlinear processes.

The slab geometry, on the other hand, completely eliminates stress induced birefringence by slab symmetry. If a zig-zag optical path is used, then the stress and thermal induced focusing is also eliminated. This leaves stress fracture as the only design limitation on the average power loading of the slab and thus on the available average output power. For LHC-8 glass, the thermal loading limit set by fracture induced breakage is 2000 W for an 8.2 mm x 25 mm x 15 cm glass slab. At this loading, the slab can operate at up to 5 Hz repetition rate and store up to 12 J of optical energy at 3.75% storage efficiency. Clearly the slab geometry offers a significant performance improvement over the usual rod geometry approach.

B. Nd:Glass Slab Measurements

The advantages of the zig-zag slab geometry have been known for more than a decade.¹ Only recently, however, has the technology for fabricating the slabs become widely available. The demands of the laser fusion research effort have pushed the fabrication and optical coating technology to the present status where slab fabrication is possible at a reasonable cost.

To take full advantage of the slab geometry in laser system design, we have developed a computer program that calculates the thermal profile of the slab, the induced stresses, the stress induced depolarization, and ray traces the zig-zag optical path through the slab. The program displays the results and can be used as an interactive design tool.

To be useful the computer model must be carefully calibrated and verified. We have accomplished verification, where possible, by comparison with analytical solutions to the thermal and stress equations. However, a test-bed Nd:Glass slab laser source was designed and constructed to provide calibration and quantitative verification of the model. Measurements using the test-bed laser system have verified predictions of the model and have shown that the slab geometry approach does, in practice, provide the projected advantages of elimination of birefringence and thermal and stress induced focusing.

The calculated stresses in the thermally loaded slab are an example of the model capability. Figure 3 shows the compression and tension field in the slab assuming uniform pumping on the y faces. From the stress field, the depolarization can be calculated and displayed as shown in Fig. 4. Note that the peak depolarization is predicted to be 32% while the average depolarization over the slab area is near 5%. Figure 5 shows a plot of predicted depolarization (solid curve) and measured depolarization (dots) at 1600 W average flashlamp power loading of the slab.¹⁰ The excellent agreement verified a number of aspects of the model including the calculated stress field, depolarization and optical ray tracing along the zig-zag path.

Figure 3—Calculated tensional and compressional stresses in a pumped glass slab assuming uniform pumping on the y faces. The slab is in compression in the center and tension at the edges. The tensional stress at the surface eventually leads to fracture of the slab.

Figure 4—Calculated depolarization for a pumped glass slab assuming uniform pumping on the y faces. The maximum depolarization is near 12%. Note that over a large region of the slab the depolarization is insignificant.

Using the slab test-bed laser we have completed measurements of gain, energy storage efficiency, pumping uniformity, depolarization, beam divergence and quality, thermal induced end effects and coolant effects on focusing, tuning, Q-switch oscillator operation, and second harmonic generation.⁹

The test-bed slab laser has operated as a long pulse oscillator at 3.75% storage efficiency, 2.0% slope efficiency and 1.6% wall plug efficiency. Typical output data for extraction from the entire slab volume is shown in Fig. 6a. We have used the test-bed slab laser to verify, by far field diffraction measurements, that the beam quality of the slab is diffraction limited. We have operated a slab glass oscillator using both an unstable resonator³ and a radial birefringent resonator design.¹¹ Figure 6b shows the output pulse energy free running and Q-switched for the 6 mm diameter oscillator mode volume.

We plan to follow the oscillator by a pre-amplifier in the same slab to generate 1.2 J and by an amplifier in a second identical slab to generate over 6 J per pulse at 5 Hz repetition rate. We have previously demonstrated tuning over a $\pm 100 \text{ cm}^{-1}$ range with a prism beam expander and grating. We expect efficient nonlinear frequency extension via SHG and Raman processes due to the diffraction limited

polarized output beam quality. The theoretical and experimental results for the slab laser are being prepared for presentation and publication.¹²

Figure 5--Predicted and measured depolarization for a pumped glass slab. The oscillations are caused by stress vector rotation combined with the zig-zag optical path through the slab.

Future slab laser research will involve the completion of a second generation slab laser system with more efficient flashlamp pumping, an optimized slab thickness and improved resonator/amplifier designs. The improved slab glass laser system will be used in remote sensing measurements in the near infrared.

C. Nd:YAG Slab Laser Measurements

The slab geometry can also be applied to crystalline laser systems. We have carried out preliminary measurements with a cw lamp pumped Nd:YAG slab oscillator. These measurements have shown that thermal and stress induced

focusing can be eliminated with the zig-zag slab geometry in Nd:YAG at up to 4 kW of flashlamp average power. This level of pumping is over six times that typically used for Q-switched, high power, pulsed Nd:YAG unstable resonator laser systems. The present pumping limit is set by the maximum power provided by our currently available power supply and not by the thermal limitations of the Nd:YAG slab.

(a)

(b)

Figure 6.

- a--Measured long pulse output energy and average power from the test-bed slab laser vs input flashlamp energy at 2.5 Hz repetition rate. The 1500 W average flashlamp power is below the measured 2000 W stress fracture limit for the present 8.3 mm x 25 mm x 15 cm long LHG-5 glass slab.
- b--Measured Q-switched output energy for a 6 mm diameter beam, unstable resonator oscillator.

We have also verified that the slab geometry completely eliminates stress induced birefringence in Nd:YAG.¹³ This is important for applications where Nd:YAG is to be frequency shifted by nonlinear processes. Work is continuing on the slab geometry applied to crystalline laser host materials.

In summary, the slab geometry approach offers more than an order of magnitude improvement in laser performance for both Nd:Glass and Nd:YAG laser systems. Recent model and test-bed laser experiments have verified that the expected improvements are realizable in practice.

III. SINGLE FREQUENCY Nd:YAG OSCILLATOR/AMPLIFIER SYSTEM

A. Introduction

The tremendous progress of coherent LIDAR measurements at the CO₂ wavelength range² has sparked an interest in long range depth resolved wind measurements using coherent LIDAR. An examination of the measurement system shows that there are advantages to be gained by using wavelengths shorter than 10 μm . These advantages include increased backscatter by more than two orders of magnitude at 1 μm as opposed to 10 μm , improved depth resolution, access to room temperature silicon diode detectors with avalanche gain, and solid state transmitters with demonstrated long operational lifetimes and small volume and weight. The principal difficulty in the approach to shorter wavelength coherent LIDAR measurements was the unknown bandwidth of the transmitter due to the unknown thermally induced chirp rate in the solid state laser host material.

During the past year we have pursued the design of a single axial mode Nd:YAG oscillator with the goal of demonstrating a frequency stability adequate for wind velocity measurements by Doppler velocimetry in the atmosphere.

B. Nd:YAG Oscillator Design

Our research efforts with single frequency Nd:YAG oscillators has clearly shown that Nd:YAG is not homogeneously saturated and that special steps such as injection locking¹⁴ must be taken to insure single mode operation. We also learned previously that the Nd:YAG chirp rate was less than 9 MHz for pulsed flashlamp excitation. Thus there was a possibility that the chirp rate in Nd:YAG could, in fact, be much less than 9 MHz and that linewidths of less than 1 MHz required for wind measurements could be achieved.

We have designed a quasi-cw flashlamp pumped, very short cavity, Nd:YAG TEM₀₀ mode oscillator source to test the frequency linewidth limitations. The oscillator is shown schematically in Fig. 7. The cavity physical length is 7.5 cm. The optical length is 10 cm due to the 2.0 cm Nd:YAG rod and thus the axial mode spacing is 1.5 GHz. A single 2 mm thick fused silica tilted etalon, with a finesse of 7 is adequate to select a single axial mode under the very broad 10 cm⁻¹ Nd:YAG gain curve.

Figure 7—Schematic of the single axial mode Nd:YAG oscillator showing resonator mirrors (1,9), YAG rod (4), quarter wave plates (2,5), flashlamp (3), Brewster polarizer (6), etalon (7), LiNbO₃ phase modulator (8), piezoelectric stack (10), and invar resonator spacers (11).

The flashlamp is simmered and pulsed for a 3-5 msec period at 10 Hz repetition rate. To generate constant power output during the quasi-cw pumping period, the flashlamp current must be increased during the pulse as shown in Fig. 8a. Note that the laser oscillator initially spikes when threshold is reached, but that the spiking behavior decays to steady state output in 240 μ sec as expected.

The laser output frequency can be stabilized relative to the tilted etalon pass band by measuring the output power vs time as originally noted by Kuizenga.¹⁵ The power variation is due to the chirp of the axial mode frequency relative to the etalon pass band and is one approach to determining the chirp rate. The chirp rate can also be measured by monitoring the laser output power after a high resolution confocal interferometer spectrum analyzer as shown in Fig. 8b. The position of the peak can be measured as a function of bias voltage on the piezoelectric stack of the resonator to yield an accurate measurement of the chirp rate. Both measurements showed that the present Nd:YAG oscillator has a chirp rate of 30 kHz per 1 micro-second.

This chirp rate is very constant from pulse-to-pulse and can be compensated by inducing a ramp voltage of 2 V per millisecond on the laser resonator piezoelectric stack. The result of this procedure is to stabilize the output frequency over the 3 millisecond duration as shown in Fig. 8c. The remaining oscillations in amplitude correspond to acoustic induced cavity length variations that in turn yield a $\pm$ 20 MHz pulse-to-pulse free running laser stability.

We are in the process of completing a locking loop to stabilize the Nd:YAG output frequency onto a 10 cm confocal interferometer with a 15 MHz passband. We expect to demonstrate a closed loop frequency stability of less than 1 MHz using a combination of a 1 kHz bandwidth feedback to the piezoelectric controlled mirror and a 1 MHz bandwidth feedback to a LiNbO₃ phase modulator within the Nd:YAG oscillator cavity.

Figure 8a.

Upper trace shows the quasi-cw single axial mode Nd:YAG laser output at 0.1 W power level. The lower trace shows the pumping lamp current with ramp compensation to achieve constant laser output power.

Figure 8b.

The upper trace shows the laser output power for the 3 msec pulse. The lower trace shows the output power following a 10 cm, $R=99.7\%$ confocal interferometer spectrum analyzer. Measurement of the pulse width or delay shows that the chirp rate is 30 kHz per microsecond.

Figure 8c.

Upper trace is laser output power. The lower trace is the laser power detected after the confocal interferometer while the chirp is compensated by a 2V/msec ramp on the PZT. Acoustically induced vibrations lead to the power and frequency fluctuations which are less than ± 20 MHz on a pulse-to-pulse basis.

The 3 millisecond quasi-cw operation was selected so that an early part of the output could be selected by a half-wave electro-optic switch and amplified by a Nd:YAG amplifier chain. The remaining part of the pulse is then available for use as the local oscillator for the heterodyne measurement for ranges up to 450 km. Longer pulse lengths are easily possible so that measurements from space platforms at 1000 km altitude are feasible. The quasi-cw operation significantly reduces the power consumption of the oscillator. The present system requires 30 W average power into the flashlamps while a cw lamp pumped oscillator would require close to 1000 W to achieve the same performance.

The present Nd:YAG oscillator generates 0.1 W of output power. We have demonstrated a double pass amplifier with a gain of 500 that utilized a 4 mm diameter Nd:YAG rod pumped by a pulsed flashlamp. We have verified that the laser linewidth is not broadened by the pre-amplifier. We expect, in the future, to demonstrate amplification to pulse energies of greater than 300 mJ in a 1 microsecond pulse at 10 Hz repetition rate in a rod geometry Nd:YAG system. The use of slab geometry offers an order of magnitude improvement without sacrificing beam quality or frequency stability.

In summary, we have demonstrated that a single frequency Nd:YAG oscillator operating in a 3 msec quasi-cw mode has a chirp rate of 30 kHz per microsecond and a free running stability of ± 20 MHz. The chirp can be easily compensated thus giving adequate frequency stability for wind velocity measurements by coherent LIDAR.

We plan to pursue the Nd:YAG source improvements and to apply the system to atmospheric wind studies. In the future, diode laser pumped Nd:YAG sources¹⁶ offer the possibility of an efficient, long term operation, space qualified transmitter source for global wind velocity measurements.

IV. CONCLUSION

We have pursued the study of advanced solid state laser concepts with the goal of meeting remote sensing transmitter requirements for future LIDAR systems. The frequency shifted, tunable glass laser source, using the slab geometry approach, offers the potential for a high pulse energy, high average power solid state transmitter without the need for a parametric oscillator or dye laser tunable source. The current Stanford test-bed slab laser source has a design goal of 6 J per pulse at 5 Hz with greater than 1% wall plug efficiency. Advanced slab glass laser designs, such as the system presently under construction at the Swiss Institute of Nuclear Research for measurements at 6.0 μ m wavelength of the Lamb shift in the μ p hydrogen atom,¹⁷ call for 10 J of output energy at 50 Hz repetition rate or 500 W of average output power. Clearly these next generation laser sources will have a major impact on the tunable LIDAR measurement capability.

The demonstration of a small chirp rate in a Nd:YAG single axial mode oscillator opens the possibility for remote wind measurements by coherent LIDAR at 1.06 μ m. The advantages of shorter wavelength and an all solid state transmitter offer the possibility of global wind field measurements from satellite platforms.

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