HIGH ENERGY EFFICIENT SOLID STATE LASER SOURCES

Semiannual Progress Report
for the period ending
Mar. 31, 1987

NASA Grant NAG 1-182

Robert L. Byer
Principal Investigator

Ginzton Laboratory Report No. 4188
April 1987

Edward L. Ginzton Laboratory of Physics
W.W. Hansen Laboratories
Stanford University
Stanford, California 94305
HIGH ENERGY EFFICIENT SOLID STATE LASER SOURCES

Robert L. Byer
Applied Physics Department
Stanford University
Stanford, California 94305

ABSTRACT

We continue our investigations of diode-laser-pumped solid-state laser oscillators and non-linear processes using them as sources. A new generation of non-planar oscillators has been fabricated, and we anticipate pushing passive linewidths to the kilohertz regime. A number of new diode-pumped laser transitions have been demonstrated in the rod configuration. Second-harmonic conversion efficiencies as high as 15% are routinely obtained in a servo-locked external resonant doubling crystal at 15 mW cw input power levels at 1064 nm.
# HIGH ENERGY EFFICIENT SOLID STATE LASER SOURCES

## Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>ii</td>
</tr>
<tr>
<td>Table of contents</td>
<td>iii</td>
</tr>
<tr>
<td>Personnel Associated with the program</td>
<td>iv</td>
</tr>
<tr>
<td>I. Introduction</td>
<td>1</td>
</tr>
<tr>
<td>II. Research Progress</td>
<td>1</td>
</tr>
<tr>
<td>III. Planned Future Research</td>
<td>3</td>
</tr>
<tr>
<td>IV. Publications and Presentations</td>
<td>6</td>
</tr>
<tr>
<td>V. Appendices</td>
<td>8</td>
</tr>
</tbody>
</table>

**"Frequency Stability and Offset Locking of a Laser-Diode-Pumped Nd:YAG Monolithic Nonplanar Ring Oscillator" (reprint)** .... 8

**"Nonradiative Processes and Blue Emission in Nd:LiYF₄" (xerox)** ........................................ 11

**"Coherent laser radar at 1.06 μm using Nd:YAG lasers" (xerox)** ................................................ 14

**"Continuous-Wave, Room-Temperature Nd:YAG Laser at 946 nm" (OSA paper FK4 October 86)** .................. 17

**"Continuous Wave Diode Laser Pumped 2-μm Ho:YAG Laser at Room Temperature" (CLEO paper FL1 April 87)** .... 18

**"Diode Laser Pumped 946-nm Nd:YAG Laser at 300 K" (CLEO paper FL3 April 87)** .............................. 21

**"External Resonant Cavity Frequency Doubling of a Diode- Pumped Nd:YAG Laser" (CLEO paper FL5 April 87)** . 24
HIGH ENERGY EFFICIENT SOLID STATE LASER SOURCES

Personnel Associated with the Program

Robert L. Byer – Principal Investigator

Robert C. Eckardt – Senior Research Associate

Eric Gustafson – Research Associate

William Kozlovsky – Graduate Student

Alan Nilsson – Graduate Student

Charles D. Nabors – Graduate Student
HIGH ENERGY EFFICIENT SOLID STATE LASER SOURCES

I. Introduction.

The objective of this program is to perform basic research and to develop technology for solid state lasers for remote sensing and communication applications. Our recent efforts have been concentrated on the refinement of the high-stability diode-pumped nonplanar ring laser design. We have also extended our research on new materials for high efficiency second harmonic generation using the diode-pumped ring laser as a source. We have explored new wavelengths for diode laser pumped operation and have successfully operated cw Nd:YAG at 946 nm and Tm:Ho:YAG at the eyesafe wavelength 2.01 µm.

The consistent theme of the program has been the use of semiconductor diode lasers for high efficiency and high frequency stability applications. Diode pumping is efficient in the sense that pump radiation is focussed entirely in the mode volume and has its energy entirely in the absorption band of the lasing ions, leading to low thresholds and outstanding slope- and wallplug efficiencies. It is also efficient in the sense that the solid state laser (or non-linear process) has far greater coherence than the pumping laser, leading to orders of magnitude improvement in spectral brightness.

Our current progress is to a large extent limited only by the availability of ever more powerful diodes. However, the pace of diode laser mass production techniques is such that we can look forward in a mere five years to 1 W single-stripe devices that can be purchased with petty cash. As these high power devices become available, the all-solid-state technology that we have been developing under this program will replace flashlamp-pumped lasers entirely.

II. Research Progress.

In the past six months the experimental work of the group has been focussed in three main areas. These are development of next-generation non-planar ring lasers in Nd:YAG and Nd:glass for frequency-stable applications, exploration and development of diode pumped miniature rod lasers in different materials and wavelengths, and resonant harmonic doubling to the green of our existing Nd:YAG lasers. We have also done modeling and design work on diode array pumped slab Nd:glass lasers.
The current generation of non-planar ring oscillators has been characterized for frequency stability by performing a frequency mixing experiment with two identical devices [a]. The lasers were offset-locked at 17 MHz in a heterodyne experiment and frequency fluctuations of less than ±40 kHz were observed for periods of 8 minutes. A major analysis and design optimization program has been completed and Nd:YAG and Nd:glass lasers have been fabricated and will soon be available for evaluation. The initial goal is to repeat the experiment described in [a] using all-new servo electronics and a vacuum isolation system to achieve an order of magnitude improvement. The vacuum system has been assembled in a refurbished lab, and the new temperature control/offset locking system electronics have been designed and will soon be prototyped.

Theoretical work has been done to model the effects of temperature, power fluctuations, magnetic field and stress on the frequency stability of the non-planar ring lasers. We have analyzed the astigmatic transverse modes of these devices, and a computer program for calculating the generalized astigmatic paraxial mode of any optical cavity has been developed. Additionally, we have explored the feasibility of monolithic unidirectional ring lasers in anisotropic crystal hosts such as YLF, BEL, FAP, and MgO:LiNbO₃.

Our recent work has led to cw diode laser pumped cw operation of Nd:YAG at 0.946 µm [b] [c], and in the Tm:Ho:YAG system at the important 2 µm wavelength [d] [e]. These systems operated at room temperature and have been modeled and studied spectroscopically to understand optimum doping levels and output couplings. The Tm:Ho:YAG system is of interest because it oscillates in an eye-safe region of the spectrum and has the potential for greater than unity pump-laser quantum efficiency.

We have also enjoyed a great deal of success recently in our efforts to resonantly double the 1.064 µm radiation from our YAG oscillators to the green [f]. In this experiment [see figure] single mode cw 1064 nm radiation from a non-planar ring laser is coupled to an externally resonant cavity formed by a nonlinear crystal with highly reflecting mirrors deposited on its ends. The circulating intensity in this structure is much higher than the incident power, which leads to high conversion efficiency for nonlinear processes. We have obtained 15% conversion efficiency to the green with only 15 mW input at 1.064 µm, which is a record. To achieve these results a special oven with 0.01°C temperature stability was constructed that also allowed a voltage of 1000 V to be applied to the crystal. This voltage was used to tune the resonant frequency of the doubler to that of the incident light by use of the electro-optic effect. We have also used this technique to lock the harmonic generator resonator frequency to the laser so that cw green light may be obtained for arbitrarily long periods.

This technique has several advantages over the intracavity method more commonly used for frequency conversion of low power devices [g] [h]. The most important are the stable output power and true single-frequency output obtainable with our technique. We have theoretically characterized this system and have designed a travelling-wave version of the doubler which will produce green light which propagates only in the forward direction, in contrast to the current standing wave system which produces light going in both directions. This should result in a factor of four improvement in output power in the green.

III. Planned Future Research.

The future planned experiments in this program follow naturally from the work described above. In the area of frequency-stable ring lasers we plan to extend the frequency stability and linewidth experiment, and apply the non-planar ring oscillator (NPRO) concept in practice to materials such as Ho:YAG, Nd:GGG, and Nd:MgO:LiNbO3. In particular, Ho:YAG is a promising system for high efficiency lasers because of its extremely long (8 msec) fluorescence lifetime. We also will experimentally study magnetic field and photoelastic stress as methods for tuning the non-planar ring lasers. These fast tuning methods will allow us to lock the optical

Experimental Set-up

Resonant External Cavity Frequency Doubling
frequency of the NPRO to external cavities for frequency doubling and linear tuning, and
to atomic or molecular frequency standards for absolute frequency stability.

In the high conversion efficiency second-harmonic generation experiment we
will fabricate and test the traveling-wave resonator. We will also use the system to
perform sub-Doppler spectroscopy of iodine with a goal of locking the laser to this
secondary frequency standard.
IV. PUBLICATIONS AND PRESENTATIONS

A. Publications


submitted for publication


B. Invited presentations


C. Contributed presentations

