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Development of State of the Art Solid State Lasers for Altimetry and other LIDAR Applications

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This report describes work performed and research accomplished through the end of 1997. During this time period, we have designed and fabricated two lasers for flight LIDAR applications to medium altitudes (Laser Vegetation Imaging System designs LVIS I and LVIS II), designed one earth orbiting LIDAR transmitter (VCL-Alt), and continued work on a high rep-rate LIDAR laser (Raster Scanned Altimeter, RASCAL). Additionally, a "White Paper" was prepared which evaluates the current state of the art of Nd:YAG lasers and projects efficiencies to the year 2004. This report is attached as Appendix I of this report.

LASER VEGETATION IMAGING SYSTEM LASERS: LVIS I & II

The medium rep-rate, high efficiency transmitter discussed in this year's proposal is the original design transmitter for LVIS and is shown in Figure 1. The design employed a short optical cavity with a porro prism (max R) end mirror with dual 15 mm long Brewster cut zig-zag slab active media. The slabs and pump diode arrays were mounted on a heat sink block which was thermally isolated form the rest of the laser and cooled via variable conductance heat pipes. Each slab was to be pumped by a 3 bar diode array stack of 60 W bars for a total quasi-CW input of 360 W. In order to obtain the desired > 2 mJ output at 500 Hz, the diode arrays would need to be operated at a 4 % duty cycle instead of the manufacturer's design 2% duty cycle. At a 4% duty cycle and 500 Hz rep-rate, the pump diodes would receive an 80 µs pump pulse to provide 28.8 mJ of optical energy to the active media for each pulse.. This should have insured > 2 mJ output at 1.0 µJ. The pump diode lifetimes are diminished by operation at the higher duty cycle, but experience with diodes manufactured by Spectra Diode Laboratories (SDL) led us to believe the science mission would be accomplished prior to any failure or significant loss of pump power due to this moderately excessive duty cycle.

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The initial version (LVIS I) never operated at the design level of performance. Requisite SDL diodes could not be obtained within the required time frame Instead a product made by Gateway Photonics Corporation (GPC) was procured and installed. These diodes could not stand the higher duty factor, and had to be run at 200 Hz Further, the stripe elements making up the arrays were crooked and therefore the pump energy could not be properly collimated into the active media. Consequently, the laser output suffered and only produced 0.5 mJ pulses of 6 ns duration at 200 Hz. When operated at 400-500 Hz, the GPC diodes failed. Another attempt to run the laser with used and damaged SDL diodes (of an estimated 150 W total power) produced ~1 mJ output with a 9 ns pulse width at 200 Hz.

Dual Oscillator Slab Alignment problems. In setting up the LVIS I laser head, it was found to be very difficult to align the diodes to the pump media while at the same time co-aligning the optical axes of the slabs with the optical cavity. This is in part because we are able to collimate the pump diode radiation into a very thin (few tenths of a mm) region in the laser crystals themselves. As a consequence, the optical cavity did not overlap as well as planned with the pumped media and the overall laser efficiency suffered.

Optical Cavity We also began experimenting with the Porro prism cavity [7] (with 1/4 wave plate end mirror and flat 40 to 60 % output coupler) versus a Concave-Convex all mirror cavity. The Porro prism cavity is touted by many to be needed for flight or space lasers as it makes an optical cavity which is less sensitive to alignment problems. Certainly, the crossed Porro cavity used in the MOLA/ SLA I laser worked very well [8]. However, that was a multi-mode laser. The Porro cavity was recently used in one prototype of the SLA II laser. That laser suffered optical damage and it may be that the Porro cavity produces hot spots when used in single mode operation under certain conditions that are not well understood.

Concave-Convex Cavity
A more stable cavity is formed by a concave-convex mirror combination which satisfies the central region of the Kogelnik stability criteria $0 \le g_1g_2 \le 1$, and is designed to have the requisite beam waist in the active media. Chesler and Maydan have shown that highly stable cavities result when the stability parameter parabola, $g_1g_2 \sim 0.5$ [9]. We tried several such cavities with LVIS I and found them to be as stable in both axes as the Porro cavity was about its best axis. Thus we are using a concave-convex cavity in the LVIS II version. Additionally, the concave -convex cavity can be designed to have a relative large beam waist near the concave mirror, which allows good coupling of the mode volume to the pumped volume.

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LVIS II

The LVIS II design is shown in Fig 2, and as is evident, bears a strong resemblance to the original. In the need to be expedient with limited resources, we have scaled back the design goals of the oscillator to produce ~ 1 mJ at 1.06 μm, and dropped the requirement for a parallel frequency doubled component. The double oscillator slabs have been replaced by a single oscillator slab pumped by a single 3 bar stack of 60 W diode arrays made by SDL . This will provide 180 W of quasi CW optical pump power or 14.4 mJ of pump energy at 4 % duty cycle when operated at 500 Hz. The same energy will be provided @ 2 % duty cycle when pumped at 250 Hz Our computer modeling predicts an output ~ 1 mJ with a pulse width of 5 ns for this pump energy when configured with an output coupler of R = 0.55. This coupler also gives the highest coupling efficiency.

LVIS II was constructed and initial tests showed the stacked collimating lenses for the pump diodes were performing below specifications. These were replaced with a single cylindrical design, which showed definite improvement . However the laser still did not perform up to specifications. It was discovered the coatings which are responsible for the total internal reflection of the side of the slab in contact with the heat sink was to blame. This is a serious problem and is being addressed most aggressively by the slab manufacturer as this report is being written. There is little doubt that it was also the primary problem of reaching >2 mJ with the LVIS I design.

EARTH ORBITING LIDAR TRANSMITTER

We have also designed a prototype laser which could be used for space based LIDAR studies of our planet, which we have named VCL_Alt. Most of the components were procured and initial assembly of the diode array package has been completed.

The design goals of VCL-Alt are:

> Output energy: 14 mJ. [12mJ at the end of a two year mission ($5 \cdot 10^9$ pulses)]
> Pulsewidth: 7 to 10 ns
> Repetition rate: 240 Hz
> Optical efficiency $\geq$ 11%
> Overall efficiency $\geq$ 5%

The design is shown in Fig 3. A ~10 cm long Brewster cut zig-zag slab is side pumped by 7 SDL, 4 bar- 60W diode arrays. Run at 94% of rated power and 2 % duty cycle, these diodes produce 140 mJ of pump energy. The pump radiation is focused into the

slab by high index Zn Selenide cylindrical collimating lenses placed immediately in front of the diodes. The design is expected to produce a 2 mm wide pump width providing an overall pump volume ~ 0.37 cm^3 and an initial inversion density of $3 \cdot 10^{17}$/cm^3. Modeling of this design yields an optimum output coupler of R ~ 0.37, a pulse width of 8.3 ns and 9 mJ TEM$_{oo}$ output if the beam waist in the active medium averages ω =0.9 mm. If ω is increased to 1mm, the model projects 12 mJ and for ω = 1.1 mm, E$_{out}$ ~14.5 mJ is projected.

The initial cavity is a concave convex design with a 99.9 reflectivity mirror of R= -35 cm and a concave out put coupler of R = 75 cm and reflectivity 0.35 separated by 52.5 cm. This produces of cavity with an average beam waist in the crystal of 0.9 mm and a g$_1 \cdot$g$_2$ value of 0.75. Assembly and testing of this design is planned to begin with a new requested funding cycle for this work.

MULTI-KILOHERTZ LASER TRANSMITTER

Work has continued on improvements for this laser known as RASCAL, for Raster Scanned Altimeter. The requirements for the 2 nd generation RASCAL transmitter are a 80 µJ /pulse @ 532 nm, a repetition rate >5 kHz and a pulse width < 5 ns.

Our approach to this laser transmitter consists of a miniature CW diode pumped Vanadate slab oscillator coupled to a multi-pass amplifier. The oscillator is a one-off Continuum SBIR product which produced the requisite repetition rate and pulse width but output energy of only 18 to 20 µJ/pulse. We had initially planned to add a second pump diode to increase the oscillator power, but have instead decided to replace the original 1.2 W diode with a fiber coupled 3 W diode which promises a somewhat higher output energy. We also made the decision on the multi-pass amplifier design.

The oscillator is shown in the left hand side of Fig. [4]. The slab is now end pumped from a fiber coupled 3 W laser diode focused into the slab prism via a microscope objective. This matches the pump beam waist to the optical cavity waist as closely as possible. The total physical path is only ~ 8 mm. in this compact design, and results in nanosecond pulse production. The angles of the pentagonal prism are chosen so that the s polarization of the laser radiation is totally internally reflected on the back side for a double pass while the p polarization is transmitted and attenuated, thus producing a 100 % s polarized output. In this configuration, we project ~ 40-50 µW of output from the oscillator into the amplifier stage. This oscillator was assembled and being aligned for testing with the 3 W diode pump, when the thermoelectric cooler (TEC) failed, and a back-up TEC cooler was broken in the process of aligning the oscillator. New TECs are on order and should arrive imminently.

The amplifier stage is shown in the upper right hand corner of Fig. 4, and is an opposing-side pumped, multi-pass wedge, which provides a total optical path of ~ 20 cm. The amplifier will be double passed and needs to provide an overall gain of only 4-5 to achieve the design goals..

The thermal lensing in the multi-pass Vanadate amp has been measured as a function of input power and is shown in Fig 5. The thermal focus is initially inversely proportional to the power, but then levels off at a slower rate above 6 W input. As the single pass length through the amplifier is only 20 cm, it is essential to keep the pump power low enough that the thermal lens can be adequately compensated using exterior lenses of modes focal lengths. The amplifier is scheduled to be connected to the oscillator stage during the next requested funding cycle and system performance measured..
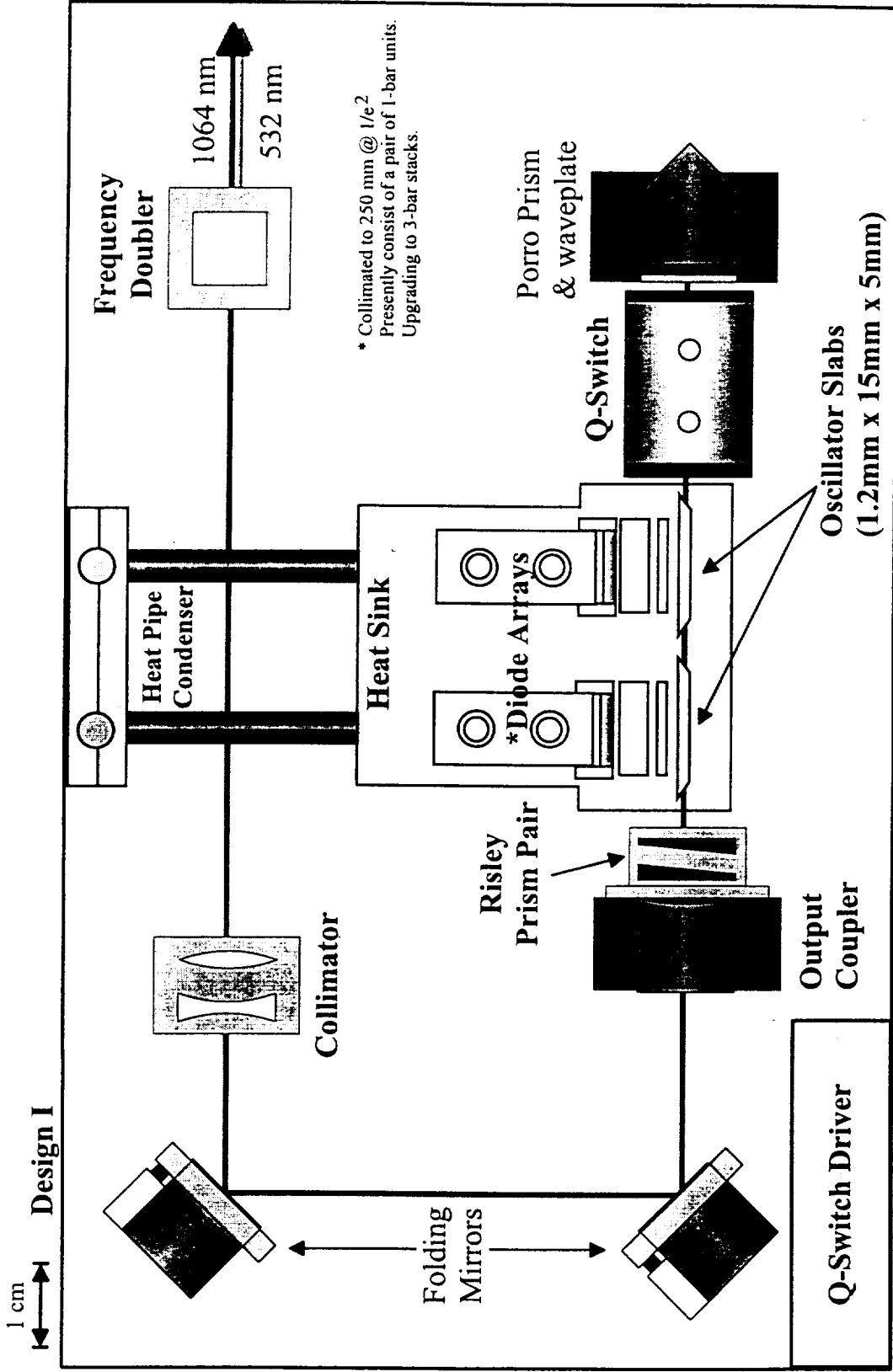
Figure 1: Lvis I

Design I

1 cm

Frequency Doubler — 1064 nm, 532 nm

*Collimated to 250 mm @ 1/e² Presently consist of a pair of 1-bar units. Upgrading to 3-bar stacks.

Porro Prism & waveplate

Q-Switch

Oscillator Slabs (1.2mm x 15mm x 5mm)

Heat Pipe Condenser

Heat Sink

*Diode Arrays

Collimator

Risley Prism Pair

Output Coupler

Folding Mirrors

Q-Switch Driver

Figure 1. Optical b ench and components of the 500 Hz, 2 ns per pulse, 2 mJ diode pumped, Nd:YAG laser altimeter transmitter. The VCHP's are shown connected to the laser head and the condensers will be thermally strapped to the enclosure wall.
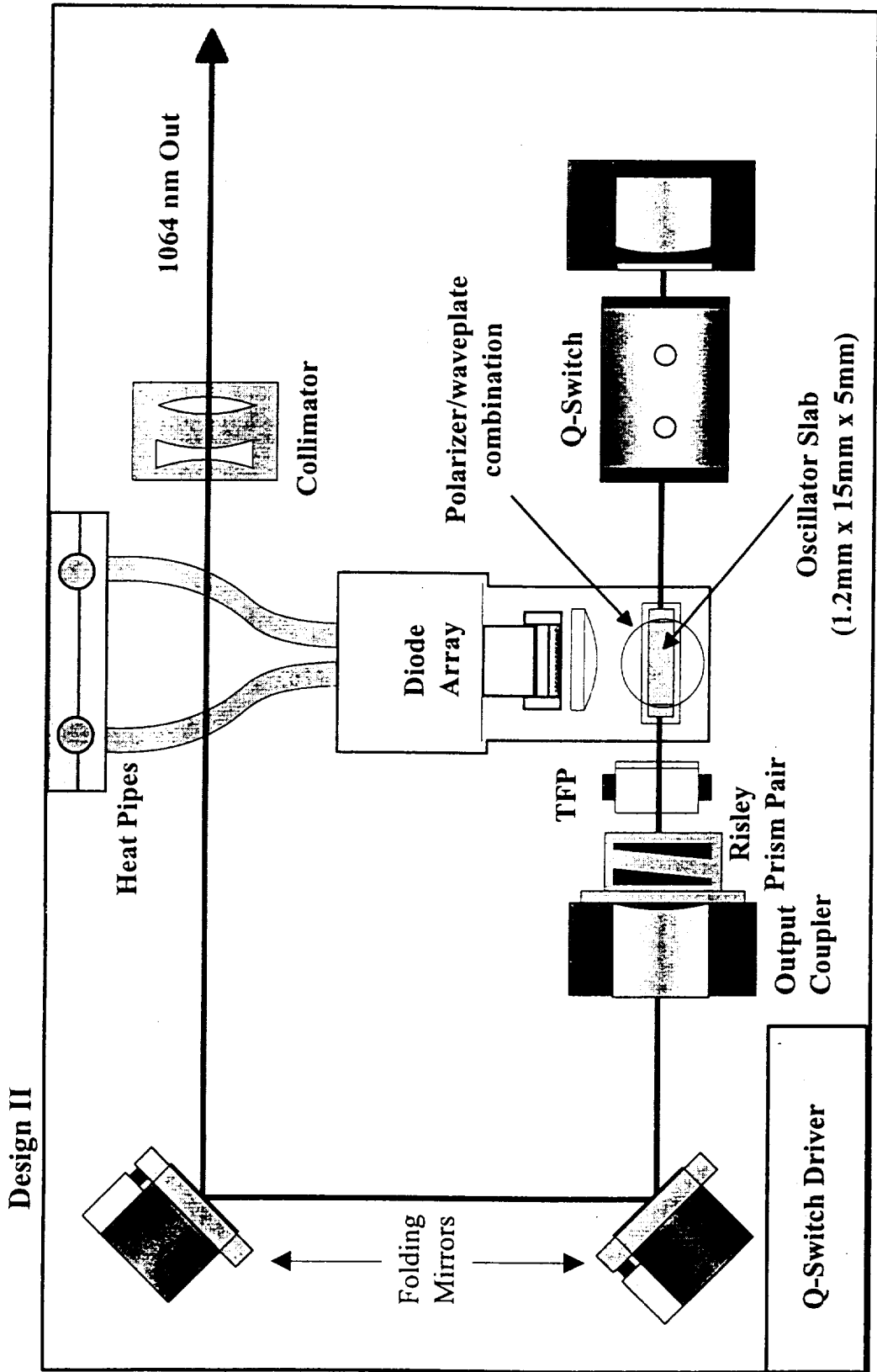
Figure 2: Lvis II

Figure 2. Optical bench and components of the redesigned 500 Hz altimeter laser altimeter transmitter. The the laser head unit has been reduced from two Nd:YAG slabs in series, each with a diode array and coupling optics, to a single unit of one slab, coupling optics and 3-bar laser diode array.

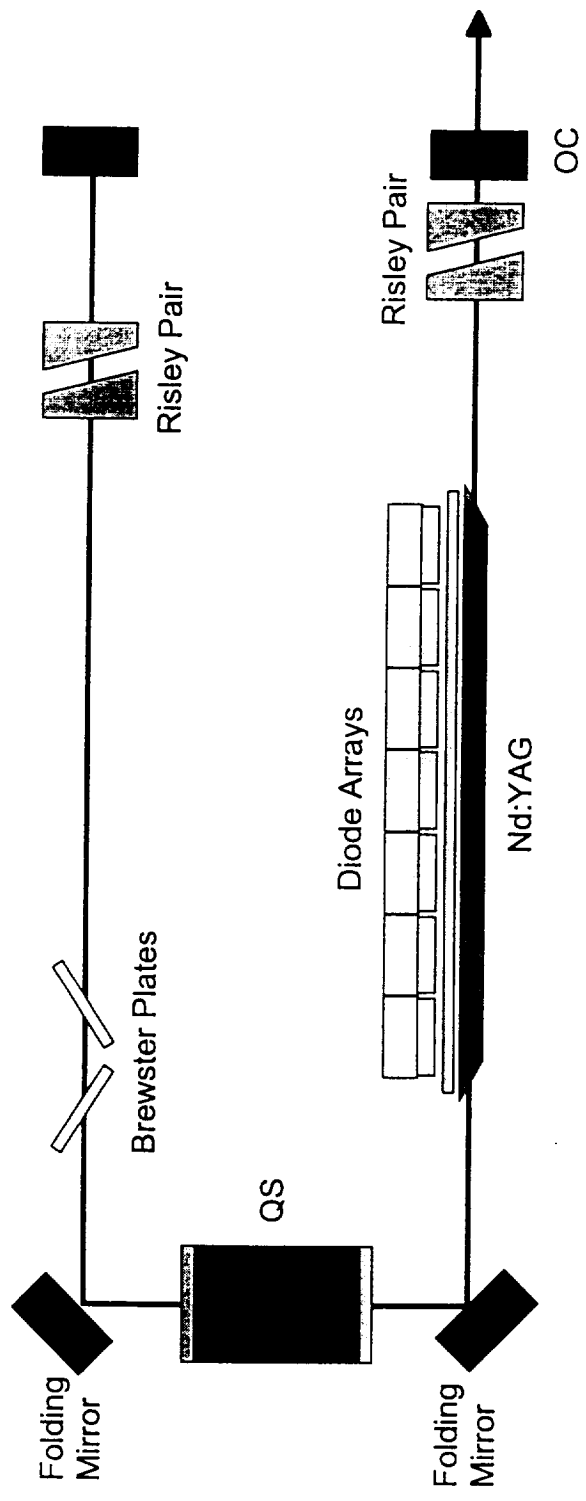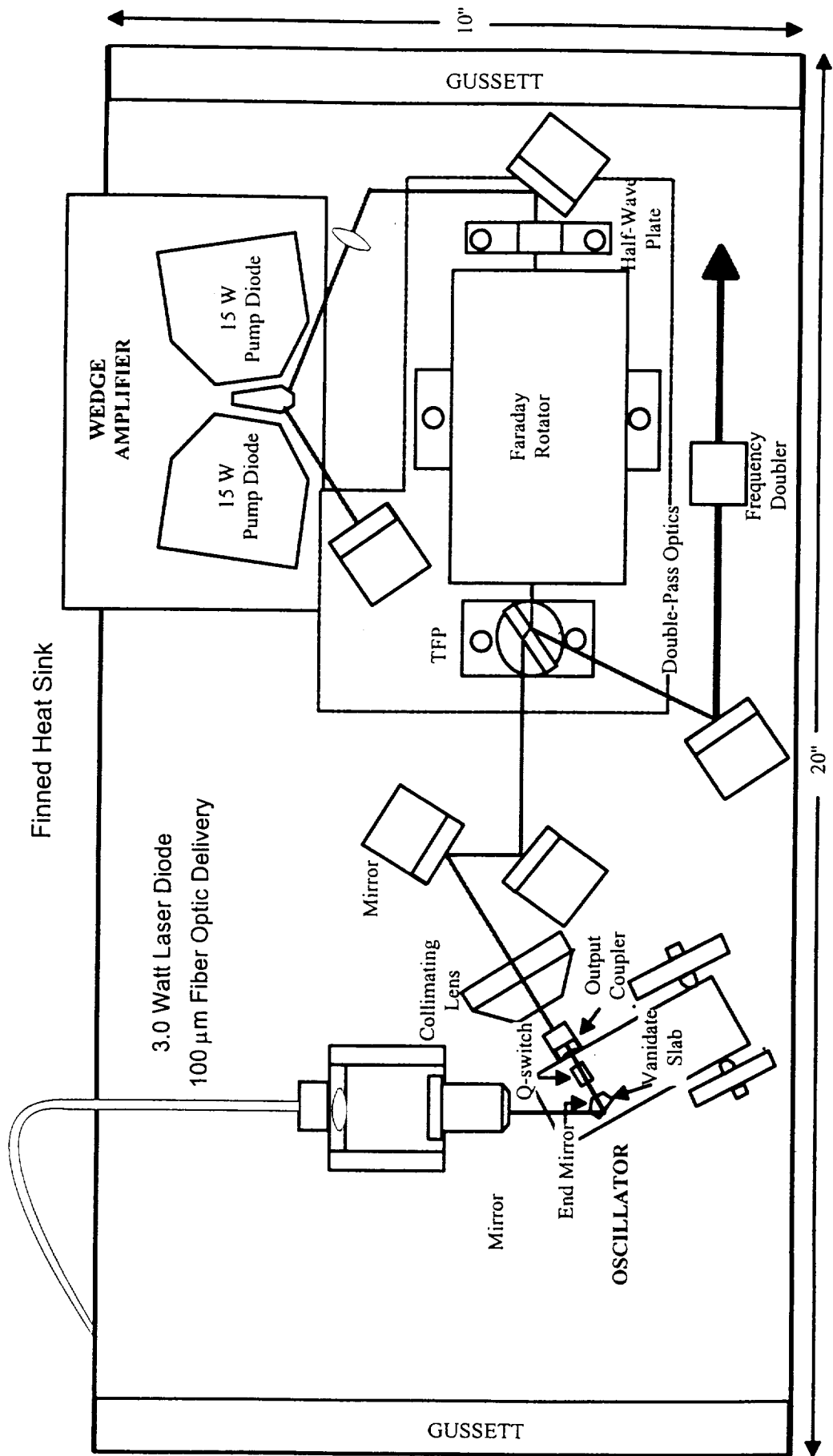# Fig. 3 VCL Alternate Prototype Laser

Figure 4: Multi-Kilohertz Transmitter

GUSSETT

Finned Heat Sink

10"

20"

WEDGE AMPLIFIER

15 W Pump Diode

15 W Pump Diode

Half-Wave Plate

Faraday Rotator

Double-Pass Optics

TFP

Frequency Doubler

3.0 Watt Laser Diode
100 μm Fiber Optic Delivery

Mirror

Collimating Lens

Output Coupler

Q-switch

Vanidate Slab
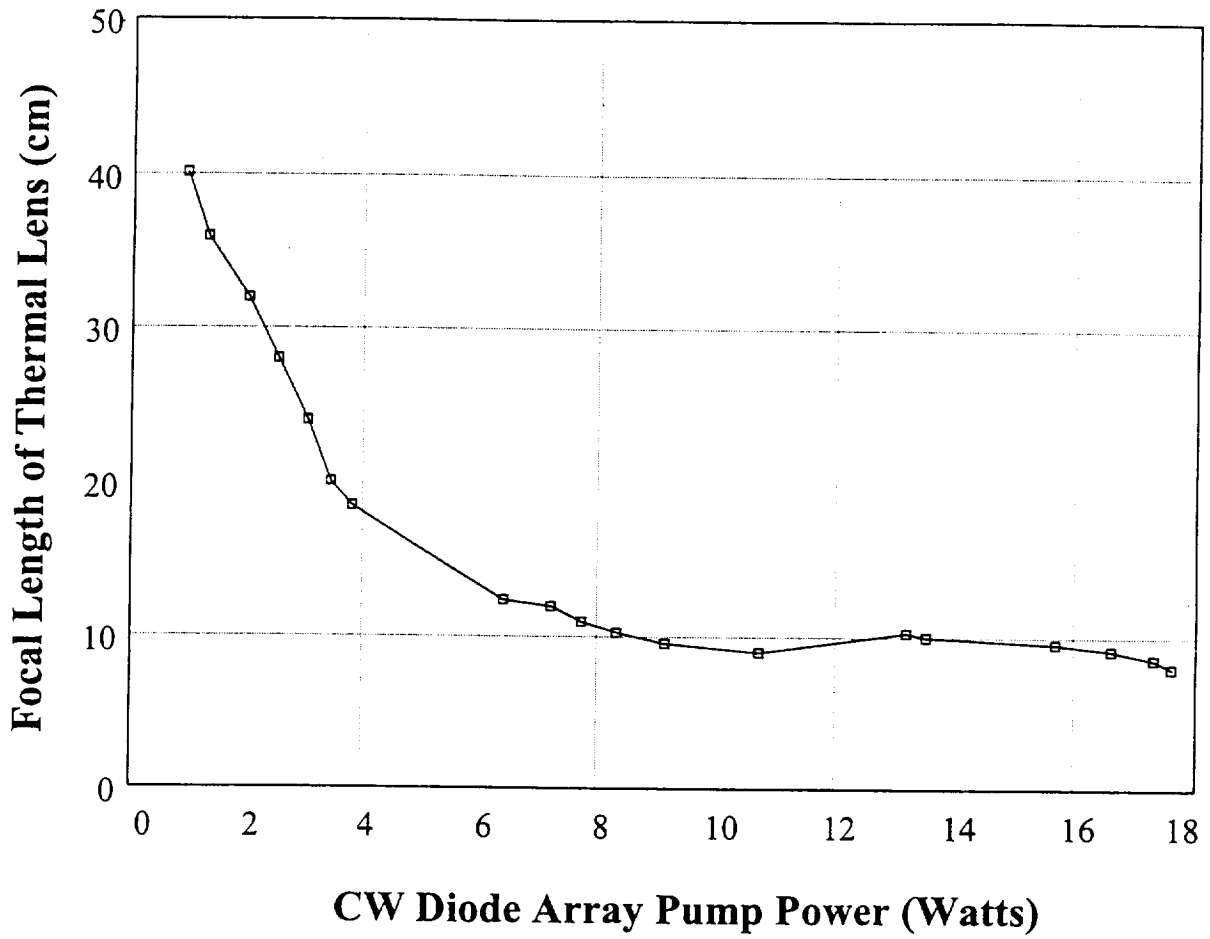
End Mirror

Mirror

OSCILLATOR

GUSSETT

Figure 5. Thermal lens measurement of Nd:Vanidate wedge amplifier slab vs. input pump power.

References

1] "Development of a Diode-Pumped, Sharp-pulsed Nd:YAG laser for Sub-Meter Resolution (SUMR) Altimetry", D. Barry Coyle and J. Bryan Blair, CLEO **11**, 14, (1993)

2] "An interactive numerical model of diode-pumped, Q-switched/cavity-dumped lasers", D. Barry Coyle, David V. Guerra and Richard B. Kay, J. Appl. Phys. **28**, 452-62 , (1995)

3] "Development of a Q-Switched/Cavity Dumped Sharp Pulsed Laser Transmitter (SPLT) for Airborne Altimetry", D. Barry Coyle and J. Bryan Blair, OSA Proceedings of Advanced Solid State Lasers, **24**, (1995).

4] "Development of a Diode-Pumped .....Nd:YAG Laser for....Altimetry", D. Barry Coyle, CLEO **11**, 14, (1993)

5] "Using echo recovery and a scanable field-of-view telescope to determine vegetation structure and sub-canopy topography over wide swaths", J. Brian Blair, David J. Harding and D. Barry Coyle,

6] "Development and test of a raster scanned Laser altimeter for high resolution airborne measurements of topography", David L. Rabine, Jack L. Bufton and Charles R. Vaughn,

7] See for example Handbook of Optics, W. Driscoll Ed.,OSA, McGraw Hill (1978)

8] "Mars observer laser altimeter: laser transmitter", R. S. Afzal, Appl. Opt. **33**, 3184, (1994)

9] "Convex-Concave Resonators for TEM_{oo} Operation of Solid State Lasers", R. B. Chesler and d. Maydan, J. Appl. Phys. **43**, 2254, (1972)