

The LIGO Pre-stabilized Laser

Rick Savage
LIGO Hanford Observatory

Sept. 2, 1997

R. Abbott

A. Abramovici

L. Cadenas

P. Fritschel (MIT)

E. Gustafson (Stanford).

J. Mason

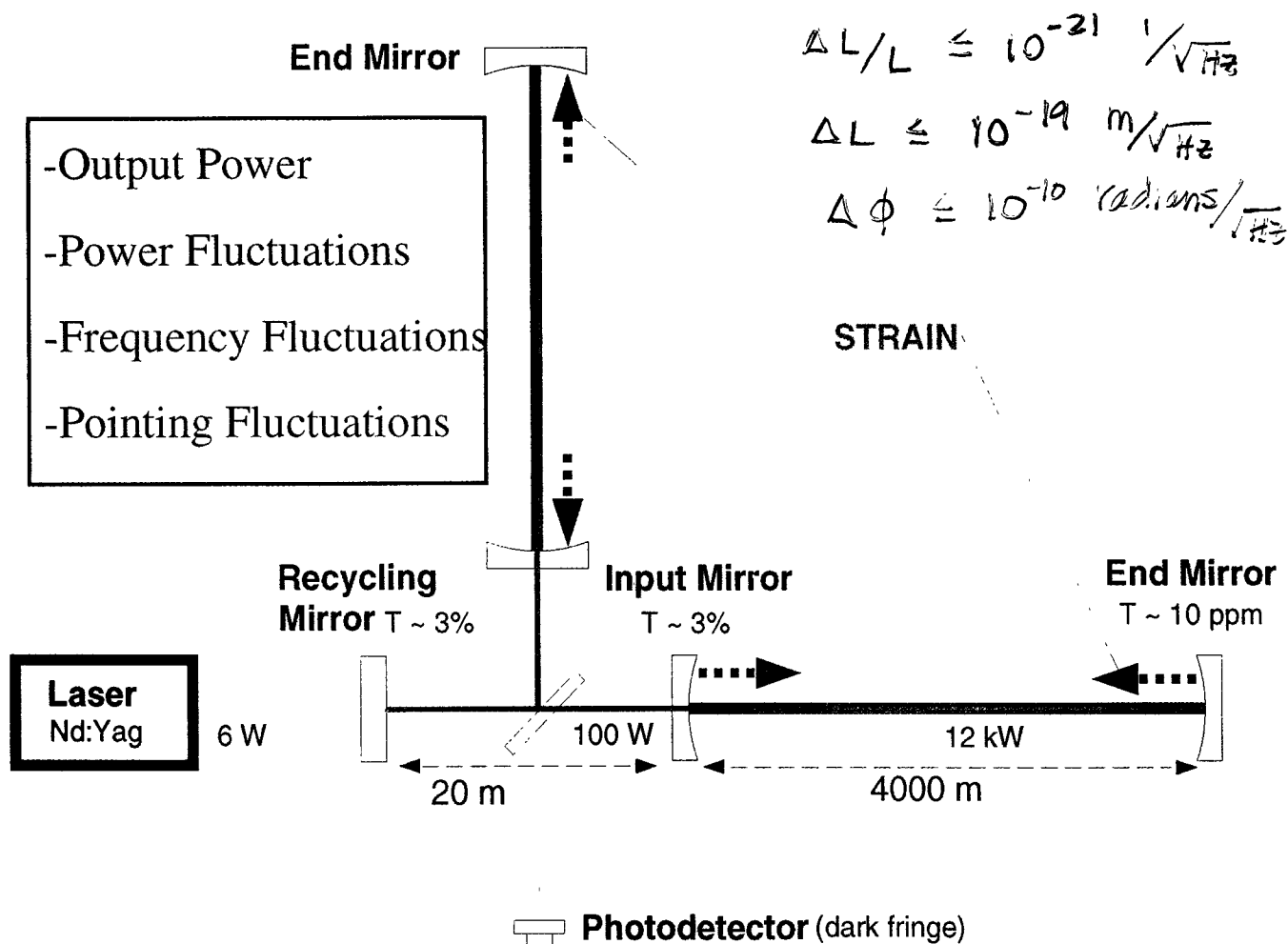
P. King

S. Seal

B. Willke (GEO)

LIGO Caltech Science Meeting

Using the Laser Radiation as the Yardstick



Power Fluctuations In the Grav. Wave Band.

$$V = A x$$

$$A \propto P = C \cdot P$$

$$V = C \cdot P \cdot x$$

$V \equiv$ gravity output signal

$A \equiv$ discriminator transfer function
in V/m

$x =$ offset from resonant length diff.

$C =$ constant

$$\frac{dV}{dt} = C \left[\frac{dP}{dt} \cdot x + P \cdot \frac{dx}{dt} \right]$$

GW noise due to power
noise coupling via
offset from resonance

Desired GW
signal

$$\text{require } \frac{dP}{dt} \cdot x \leq \frac{1}{10} P \cdot \frac{dx}{dt}$$

$$\frac{dP}{P} \leq 0.1 \frac{dx}{x}$$

$$dx \sim 10^{-19} \text{ m} / \sqrt{\text{Hz}} \text{ at } 100 \text{ Hz}$$

$x = 10^{-13} \text{ m}$ (nominal
rms cavity offset).

$$\frac{dP}{P} \text{ or } \frac{dI}{I} \leq 0.1 \frac{10^{-19} \text{ m} / \sqrt{\text{Hz}}}{10^{-13} \text{ m}} = \underline{\underline{10^{-7} / \sqrt{\text{Hz}}}}$$

Beam Pointing Fluctuations

$$* \delta L \approx 7.1 \cdot 10^{-21} \left(\frac{\psi_2}{10^{-8} \text{ rad}} \right) \left(\frac{\sqrt{\alpha^2 + (0.16\kappa)^2}}{4 \cdot 10^{-9} / \sqrt{\text{Hz}}} \right) \frac{\text{m}}{\sqrt{\text{Hz}}}$$

SRD Requirement
(1.005 rule)

Static alignment offset

relative angle fluctuations
relative disp. fluct.

$$\sqrt{\alpha^2 + (0.16\kappa)^2} \leq 4 \cdot 10^{-9} / \sqrt{\text{Hz}}$$

assume two terms contribute equally.

$$(2\alpha^2)^{1/2} \leq 4 \cdot 10^{-9} / \sqrt{\text{Hz}} \quad \alpha \leq 2.8 \cdot 10^{-9}$$

$$2(0.16\kappa)^2 \leq 4 \cdot 10^{-9} / \sqrt{\text{Hz}} \quad \kappa \leq 1.8 \cdot 10^{-8}$$

$$\alpha = \frac{\delta\theta}{\theta/2} \leq 3 \cdot 10^{-9}$$

$$\kappa = \frac{\delta x}{w_0}$$

** 12-m mode cleaner filtering of 18th higher order mode
x . 0014

$$\rightarrow \delta\theta / \theta/2 \leq 2.0 \cdot 10^{-6}$$

$$\frac{\delta x}{w_0} \leq 1.3 \cdot 10^{-5}$$

* ASC DRD Appendix 5

** IOO CDD P.13.

LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Document Type	LIGO-T950047-01 - E	<u>8/4/95</u>
<u>Evaluation of Nd:YAG(1064nm) Lasers for Use in the Initial LIGO Interferometers</u>		
<u>A. Abramovici, D. H. Shoemaker</u>		

This is an internal working note
of the LIGO Project..

California Institute of Technology
LIGO Project - MS 51-33
Pasadena CA 91125
Phone (818) 395-2129
Fax (818) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project - MS 20B-145
Cambridge, MA 01239
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

WWW: <http://www.ligo.caltech.edu/>

2 SUMMARY OF TECHNICAL MERITS

Nd:YAG is expected to be a light source which will be suitable for enhanced and advanced LIGO interferometers. In the laboratory, Nd:YAG and other solid-state lasers exist already which are suitable for engineering into 'enhanced' interferometers (with 40 W of power, equivalent to 20 W of Argon 514 nm light). In contrast, Argon lasers have no promise of more than 20% increases in power. Thus, we see a need to change to solid-state lasers shortly after commissioning of the initial LIGO interferometers.

To first order, then, we wish to anticipate that change and to test if we cannot start the initial LIGO interferometers with a light source and wavelength which would allow an adiabatic change to higher power. This can save schedule, and reduce the net cost, of arriving at an enhanced level of shot-noise limited sensitivity.

A second reason to investigate Nd:YAG lasers at 1064 nm at this time is to evaluate possible performance advantages from the different wavelength. Relaxed mirror specifications, and lower Rayleigh scatter in the substrates, are examples.

In summary, there do not seem to be any aspects of the interferometer performance or engineering difficulty which would be significantly adversely impacted by a change to 1064 nm and Nd:YAG for the initial LIGO interferometers, and all indications that higher power lasers will be in parallel development (driven by a rapidly growing industrial demand). There are a number of places where more in-house effort will be required, to characterize new components, but sharing with laser groups and other GW groups can reduce this burden.

The tables below summarize the differences between a Argon-514nm interferometer and a Nd:YAG-1.06 μ m laser. Points which can be clearly seen as disadvantages are indicated in *italics*. Details are given in Appendix B. Most categories should be self-explanatory; by 'engineering status' we mean to give a one-line summary of the availability of a commercial solution, the engineering future, the rate of progress in the field, etc.

Table 3-1: Laser Technical Summary

parameter/part	Nd:YAG Merit/Demerit	Argon Merit/Demerit
<u>power</u>	initial power available, <u>future power assured;</u> <i>~2x power required for given sensitivity</i>	initial power available; <i>no further increases prob- able.</i>
<u>efficiency</u>	several <u>10⁻²</u>	<u>10⁻⁴</u>

parameter/part	Nd:YAG Merit/Demerit	Argon Merit/Demerit
<u>mean time before failure</u>	10,000 MTBF (commercial specification) 10-20,000 MTBF (Byer experience)	8000 MTBF (commercial specification) ~2000 MTBF (LIGO experience)
<u>failure mode</u>	~20% reduction in power	<i>no light</i>
<u>raw frequency noise, 90 Hz</u>	$10^2 \text{ Hz}/\sqrt{\text{Hz}}$	$10^4 \text{ Hz}/\sqrt{\text{Hz}}$
<u>raw intensity noise, 90 Hz</u>	$10^{-6} \delta I/I \text{ } 1/\sqrt{\text{Hz}}$	$10^{-4} \delta I/I \text{ } 1/\sqrt{\text{Hz}}$
<u>raw intensity noise meets ~100 mW shot noise</u>	3 MHz	~5 MHz
<u>beam jitter</u>	not yet characterized; reported to be small	characterized
<u>engineering status</u>	<u>~\$1M+ 1 year development</u>	<u>ready</u>
<u>future development</u>	<u>growing market</u>	<u>static to declining market</u>

Table 3-2: Modulator (Input Optics) Technical Summary

parameter/part	Nd:YAG Merit/Demerit	Argon Merit/Demerit
power handling	to 20 watts	to 5 watts
sensitivity	210 volts/ π , 1.06 μm	1000 volts/ π , 514 nm
frequency range	to 100 MHz	to 60 MHz (in pairs)
engineering status	commercial item	commercial item

Table 3-3: Core Optics Technical Summary

parameter/part	Nd:YAG Merit/Demerit	Argon Merit/Demerit
mirror size	<i>back mirror >27 cm</i>	<25 cm \rightarrow <i><20cm</i>
figure requirements (sample requirement)	Argon * $\sqrt{2}$ $=\lambda_{514}/424$	$\lambda_{514}/600$
required coating uniformity (random errors)	0.1%	0.1%

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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Impact of Replacing Argon
Lasers with Nd:YAG Lasers

A. Abramovici, D. S. Shoemaker

California Institute of Technology
LIGO Project - MS 51-33
Pasadena CA 91125
Phone (818) 395-2129
Fax (818) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project - MS 20B-145
Cambridge, MA 01239
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

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Evaluation of Nd:YAG(1064nm) Lasers for Use in the Initial LIGO Interferometers

17 August 1995

Science Conference Room (818-395-2067)

- Barry Barish 0900 - 0930
 - Opening remarks & review of the charter for the trade study
- David Shoemaker 0930 - 1000
 - Review of findings with regard to TECHNICAL feasibility for using YAG lasers
- Discussion of technical issues 1000 - 1100
- Alex Abramovici 1100 - 1130
 - Review of findings with regard to IMPACT of making a change to YAG lasers
- LUNCH 1130 - 1200
- Discussion of programmatic issues 1200 - 1330

CALIFORNIA INSTITUTE OF TECHNOLOGY
Laser Interferometer Gravitational Wave Observatory (LIGO) Project

3rd F.

Rick Savage

To: LIGO/Distribution
From: B. Barish and G. Sanders
Phone/FAX: Ext. 6684 and 2997
Refer to: LIGO-L950722-00-M
Date: September 14, 1995

BeB./GTS/am

Subject: Lasers

We have carefully considered possible laser strategies for LIGO and are persuaded that we should switch to 1.06 μ m YAG lasers, and that this should be accomplished as quickly as possible. We believe the long term benefits to LIGO of making this switch now are considerable and are well aware of the shorter term impacts of this change. Success, therefore, depends on working together to quickly and effectively affect this change, to acquire and gain experience with YAG lasers and to research our R&D and detector programs to minimize the scheduling and other short-term impacts. To do this we must build a very strong YAG effort and we must aggressively and creatively work all the issues involved in the switch. To accomplish this, we have asked Stan Whitcomb (and he has agreed) to lead our effort on the YAG and we promise him our strong support. As soon as Stan can describe a plan for the effort the LIGO Change Control/Technical Board will be asked to formally review this change to the baseline.

This YAG decision has been made following a process that began with a presentation (at our request) by David Shoemaker at the May 1995 Science-Integration meeting. We followed that by tasking Shoemaker and Abromovici to do a more quantitative study resulting in a technical note. We invited all to participate in a discussion meeting on August 17, 1995. Following that meeting, we invited individual input and received many thoughtful replies.

There are many complex issues involved in this decision and judgement is involved in making the final decision. We have weighed heavily the long term objectives of finding the clearest path toward reaching and exceeding the initial design sensitivity of LIGO. Although others weighed different factors more heavily, we can report that there is a near consensus on whether we should make the switch.

With this decision behind us, it is crucial that now we all get behind it and work together to make it work. In a large group effort like LIGO it is essential that we bring out hard issues, carry out an open process to evaluate them, make carefully considered decisions, and then that we all get behind the decision and move on.

We thank everyone for their hard work, thoughtful input, and in advance, for their support of this important LIGO decision.

BCB:dt

cc: Chronological File

Document Control Center

InterOffice Memorandum

• May 15, 1996.

FIXED-PRICE CONTRACT
Contract No. PC198201

BETWEEN

CALIFORNIA INSTITUTE OF TECHNOLOGY
1201 E. CALIFORNIA BLVD.
PASADENA, CALIFORNIA 91125

AND

LIGHTWAVE ELECTRONICS CORPORATION
1161 San Antonio Road
Mountain View, California 94043

THIS CONTRACT FOR

Design and Fabrication of Nd³⁺ Lasers

IS A

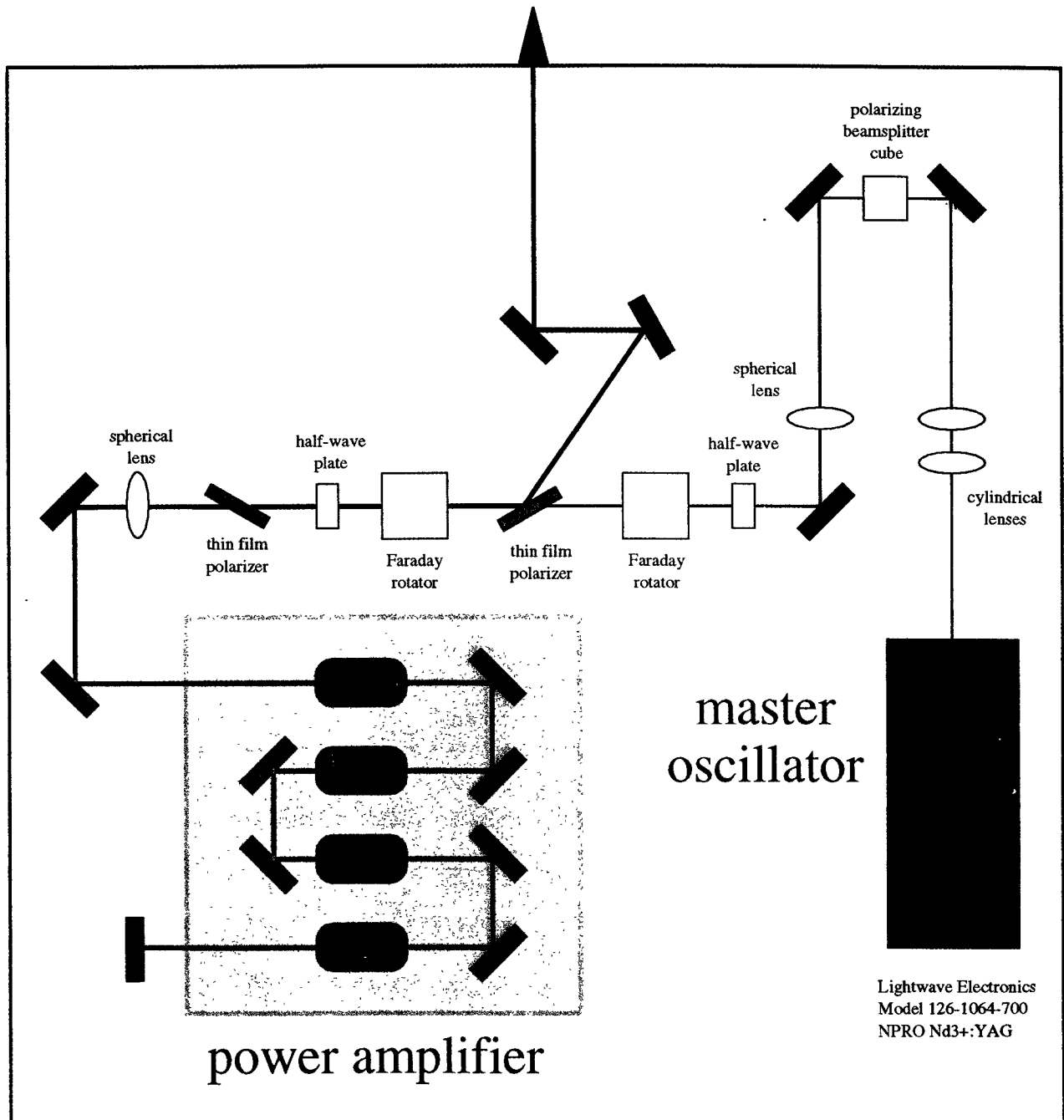
SUBCONTRACT UNDER A NATIONAL SCIENCE FOUNDATION
COOPERATIVE AGREEMENT NO. PHY-9210038

CONTRACT PRICE: \$735,424.00

LIGO-C960880-A-R

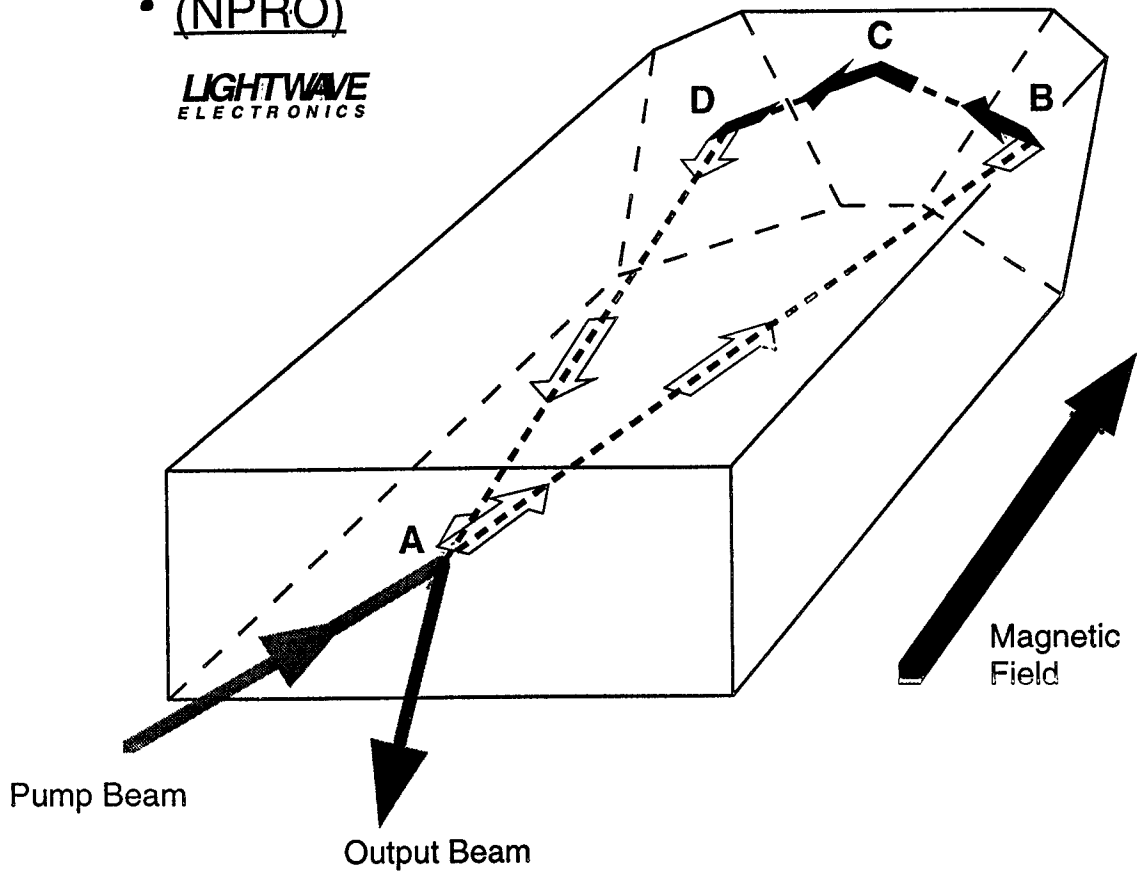
- 3 10-W Lasers
- Option for up to 5 additional lasers

LIGO 10-W Laser Schematic Diagram



Nonplanar Ring Oscillator
• (NPRO)

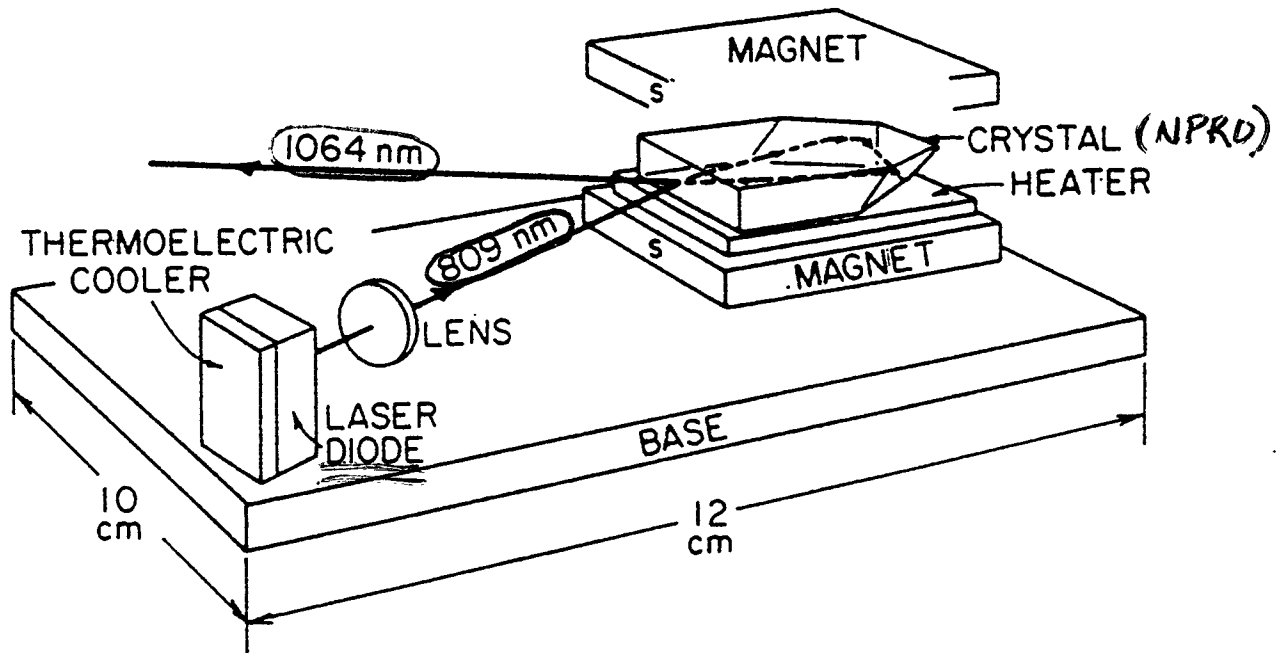
LIGHTWAVE
ELECTRONICS



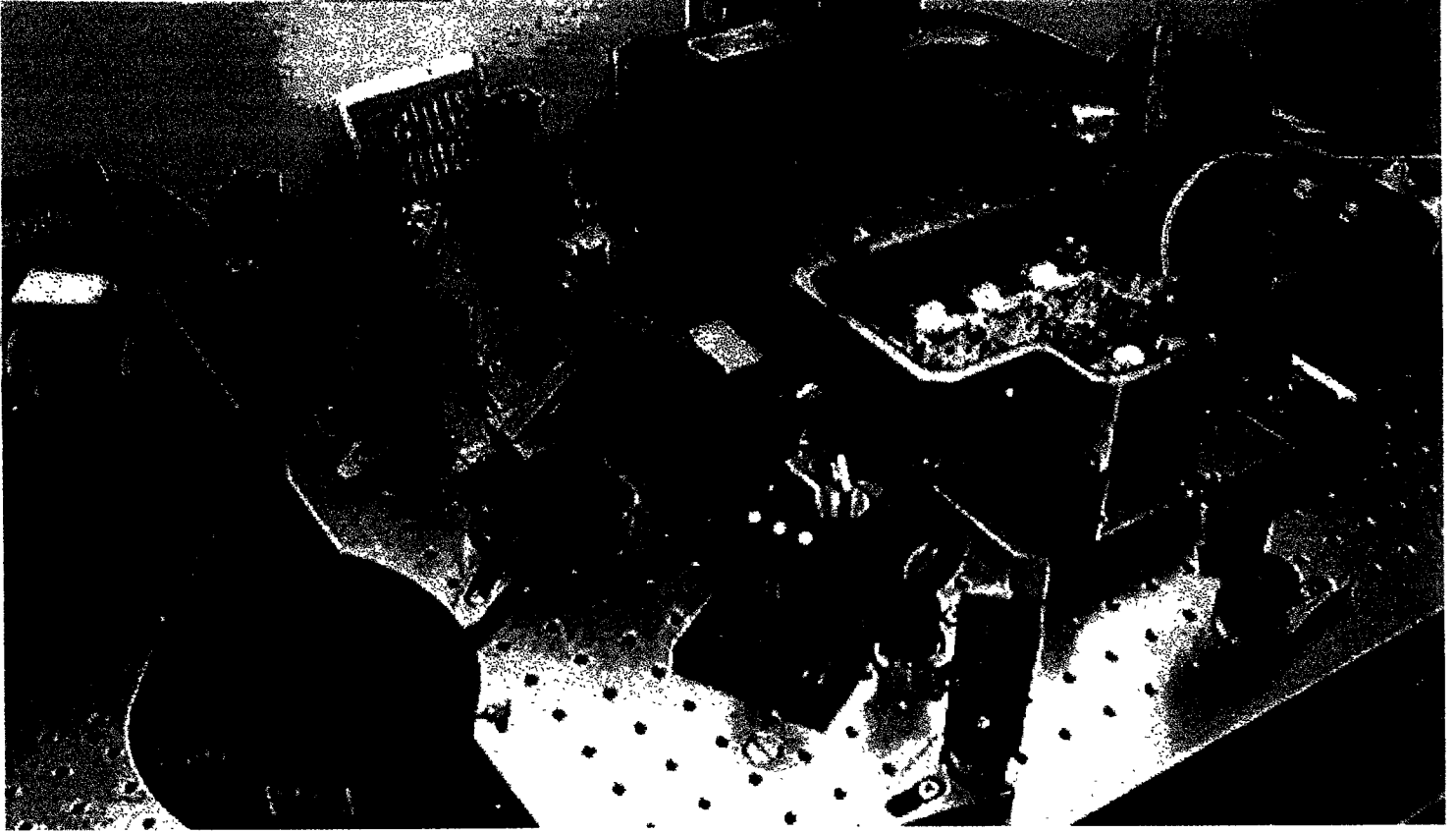
- Magnetic field enforces unidirectional operation.
- Unidirectional operation leads to single-frequency oscillation.
- Monolithic crystal design leads to stable frequency.
- No efficiency penalty relative to multi-mode lasers.
- Length of crystal: 3 mm Output power: 50 mW

Z = 31" FSR = 8.6 GHz

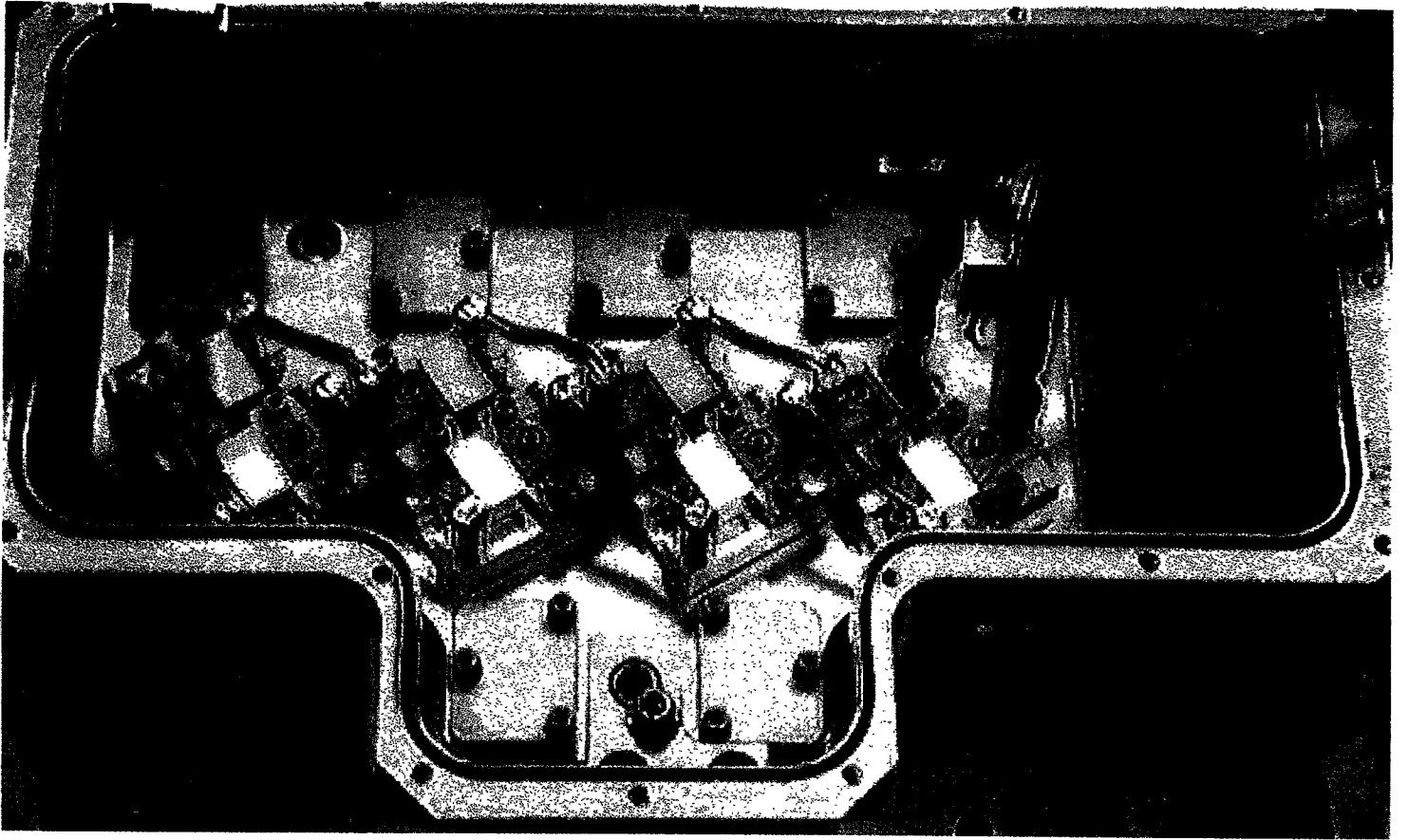
Laser diode pumped, NPRD based master oscillator



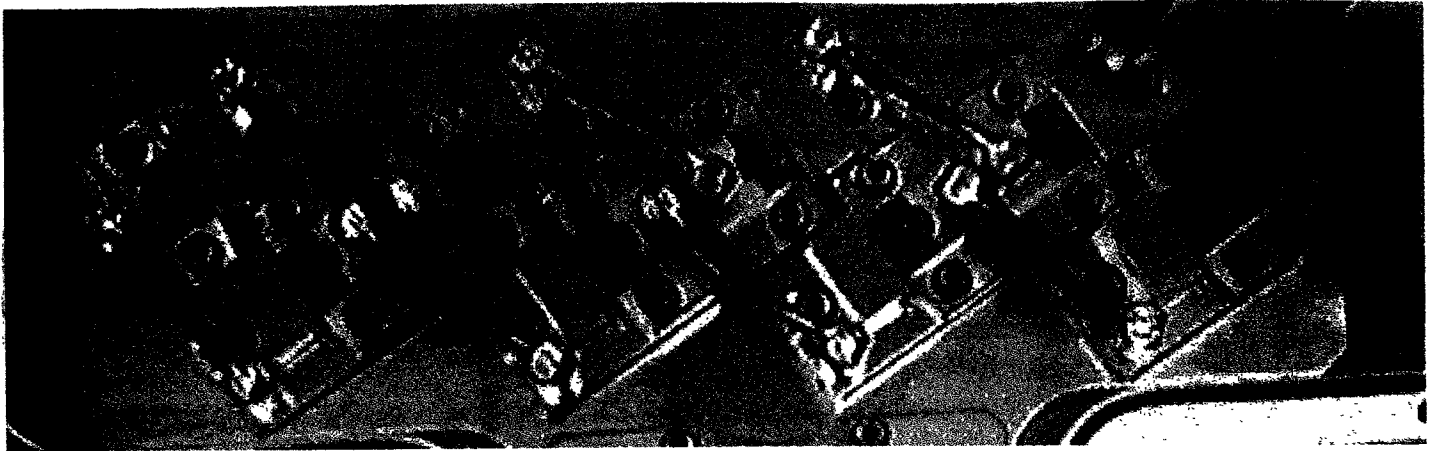
- Frequency tuning via
 - NPRD
 - Thermoelectric cooler
 - Piezoelectric transducer mounted to xtal.
- Output power tuning via pump laser diode current adjustment.
- 700 mW output power (600 mW required for 10-10 laser).



8/29/97



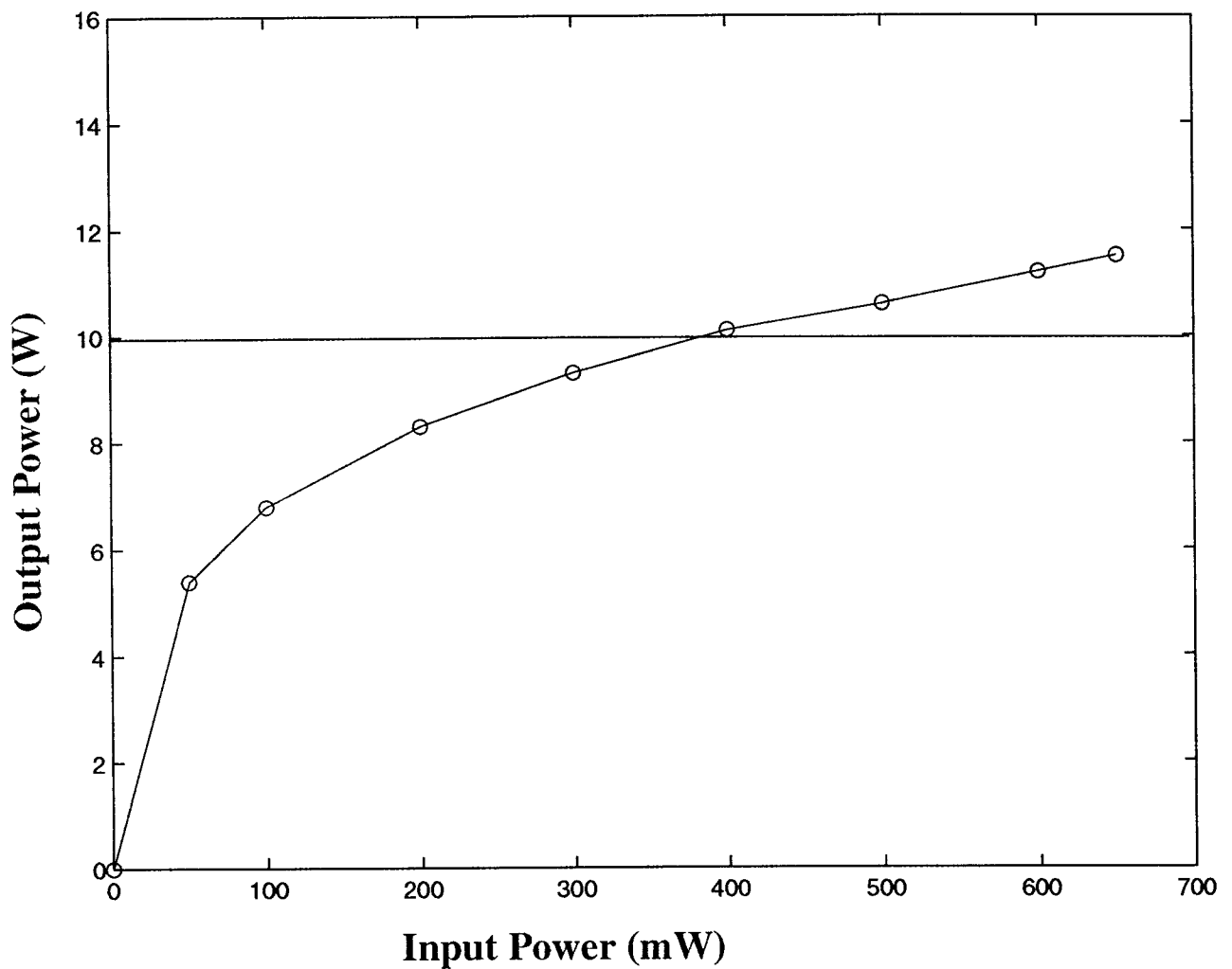
8/29/97



8/29/97

LIGO 10-W Laser Brassboard Unit Data

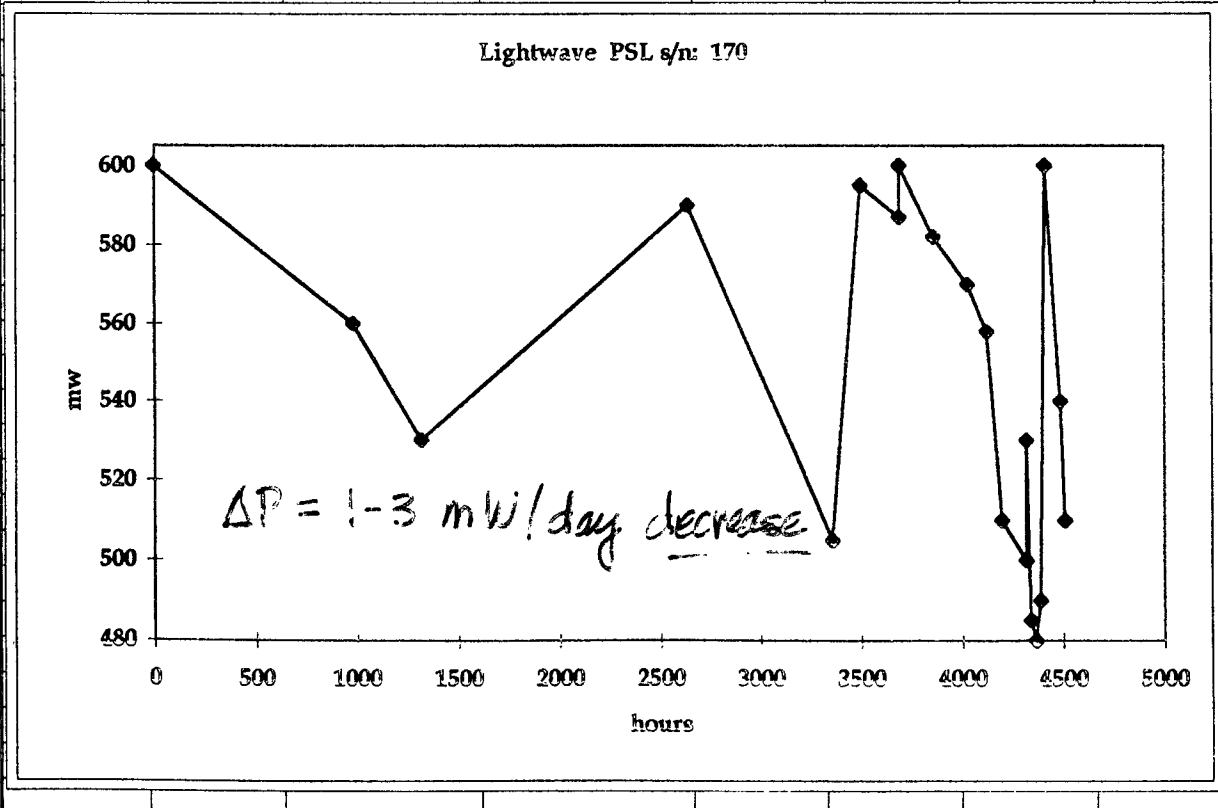
Double-Pass Output Power



LIGO 10-W Laser Performance Requirements

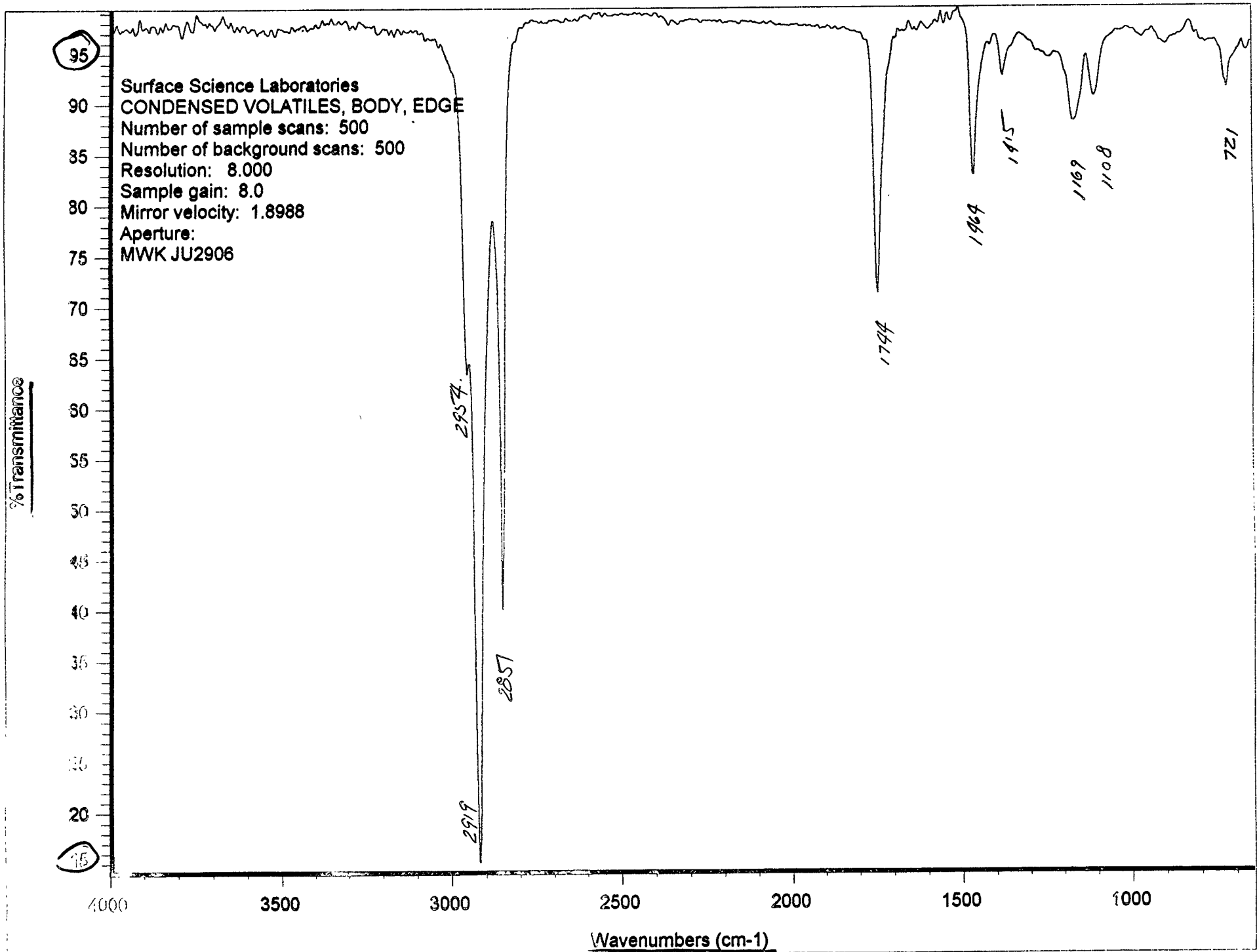
- > 10 W in circular TEM₀₀ mode
 - ›› < 1 W total in all non-TEM₀₀ modes
- Relative power fluctuations $< 10^{-5} (\text{Hz})^{-1/2}$
 - ›› 100 Hz to 10 kHz
- Within 2 dB of shot noise limit for 10 mA of photodetected current ($7 \times 10^{-9} (\text{Hz})^{-1/2}$)
 - ›› Above 24.5 MHz
- Frequency fluctuations $< 500 \times (100/f) \text{ Hz}/\sqrt{\text{Hz}}$
 - ›› 100 Hz to 10 kHz
- Relative pointing angle fluct. $< 3 \times 10^{-6} (\text{Hz})^{-1/2}$
 - ›› Above 150 Hz
- *10,000 Hours Mean Time Between Failures*

Date	Hours	Power Meter (mw)	Power Control (mw)	mw/day	Current (amps)	Adj.	psl
11/27/96	0	600	600		2.52	0	
1/7/97	984	560	600		2.52	0	
1/21/97	1320	530	600		2.52	0	
3/18/97	2640	590	595		2.52	0	
4/17/97	3360	505			2.52	adj	
4/23/97	3504	595	600		2.54	0	
5/1/97	3696	587	570		2.54	0	
5/1/97	3696	600	585		2.54	adj	
5/8/97	3864	582	570		2.54	0	
5/15/97	4032	570	555		2.54	0	
5/19/97	4128	558	548		2.54	0	
5/22/97	4200	510	511		2.5	0	
5/27/97	4320	500	496		2.5	0	off
6/2/97	4320	530	526		2.54	0	on
6/3/97	4344	485	489		2.5	0	
6/4/97	4368	480	489		2.5	0	
6/5/97	4392	490	503		2.5	0	
6/6/97	4416	600	600		2.775	adj	
6/9/97	4488	540	548		2.775	0	
6/10/97	4512	510	526		2.775	0	fail!
from 5/01 - 6/5/97		overall 696 hrs	POWER LOSS=	3.7931034	mw/day		

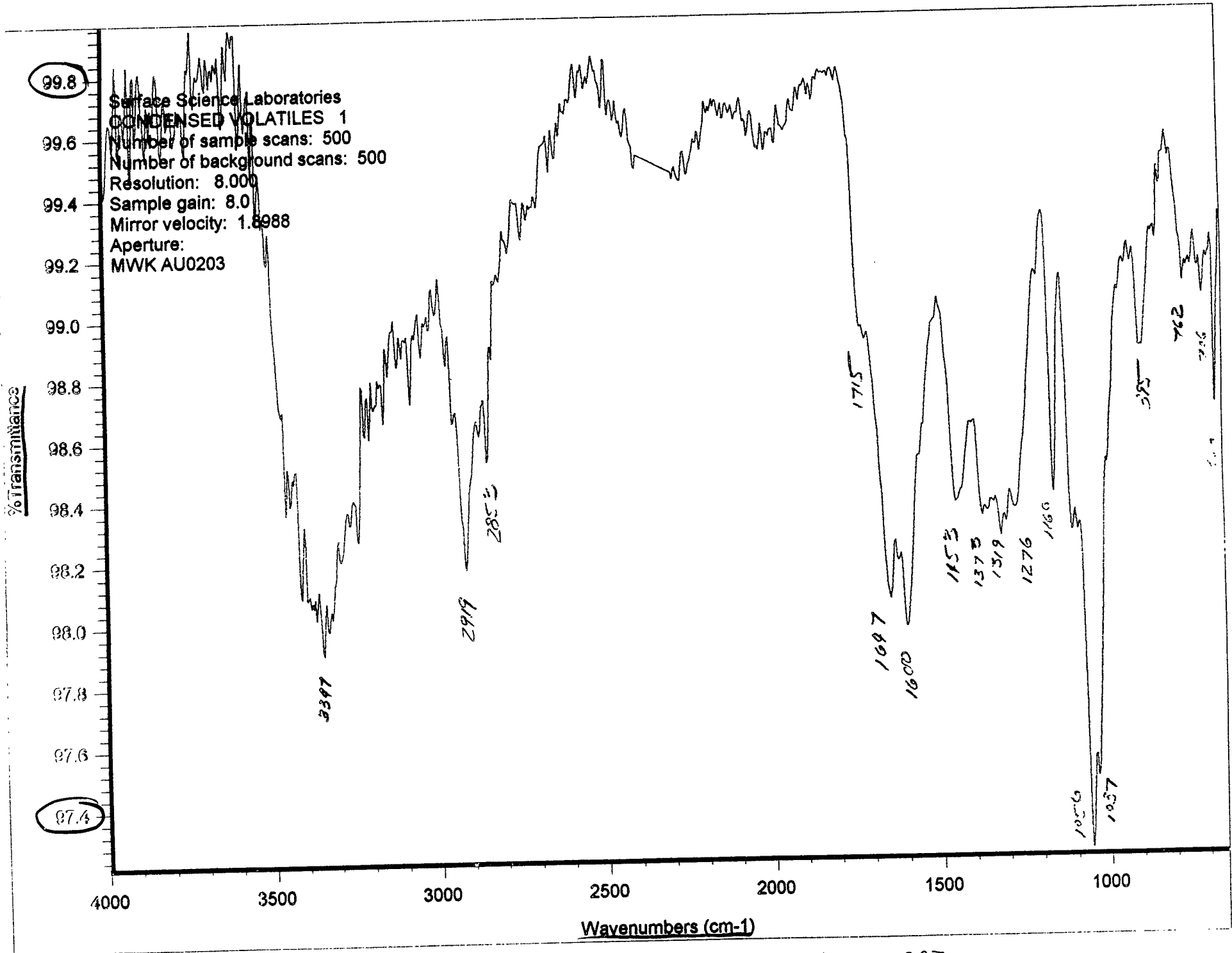


Lightwave Model 126 Reliability Investigations - Completed

- baseline condensable volatiles test 6/12/97
 - silicones, machine oil, circuit board additives
 - more aggressive cleaning, bake out.
- elimination of thermal grease and apiezon grease from build procedure 6/26/97
- baseline gas chromatography/mass spectrometry 6/27/97
 - siloxanes and cleansers
 - improved cleaning and bake out
- non-destructive analysis results from SDL 7/1/97
 - light burn spot on facet, contamination on facet
- improved cleaning and bake out procedures implemented 8/1/97
 - machined parts degreased and baked 100°C / 1 hour
 - electronics boards 100°C / 3 hours
- condensable volatiles test after new cleaning procedures 8/12/97
 - contaminants greatly reduced
- condensable volatiles test after 24 hour bake at 85°C 8/12/97
 - no contaminants detected



→ - June 18, 1997



4 - August 12, 1997

Lightwave Model 126 Reliability Investigations

Planned.

8/14/97

condensable volatiles test just above facet

waiting for test results

development of better cleaning and bake out procedures 8/13/97

degrading and new SDL diodes to JPL for surface analysis 8/22/97

in progress

SDL/Lightwave 40-diode test

7/24/97.
agreement date

20 diodes built into Model 126 lasers
20 diodes run and monitored at SDL

diode lifetime testing at Lightwave

2 diodes to be tested in Model 126 packages

2 diodes in 126 package but w/o collection lens *

2 diodes in hermetic package from SDL

1 diode from an alternate vendor

one unit has been operating for 28 days with no change (C192).

lifetime testing of Model 126 lasers for 160 10-w lasers

4 units under test - 3 built before new procedures

- 1 with improved cleaning and bake