Setting the Optical Specs for LIGO

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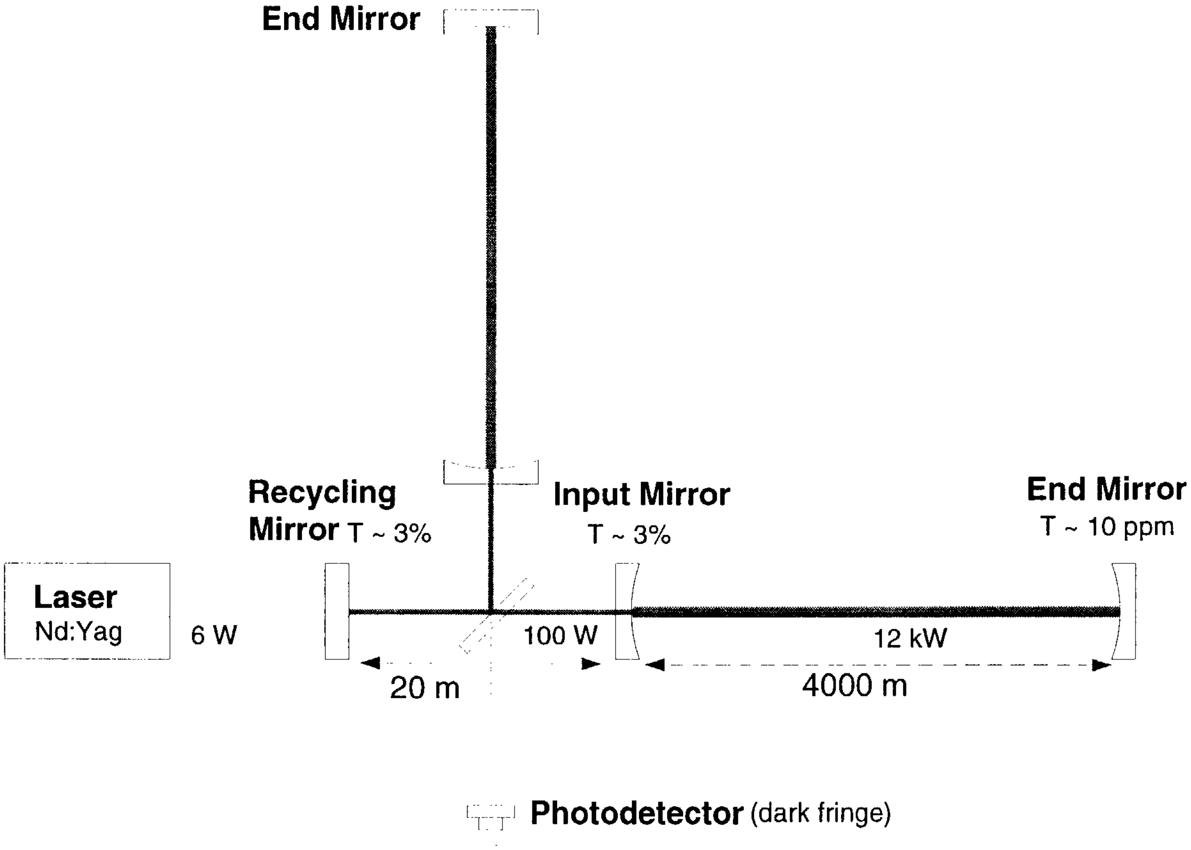
Advanced configuration

Large Optical Components ("Core Optics")

- Test Masses
  - ›› End Mirror
  - ›› Input Mirror
- Beamsplitter
- Recycling Mirror
- Total Number: 20
  - ›› WA 4km: 6 Optics
  - ›› WA 2km: 8 Optics
  - ›› LA 4km: 6 Optics
  - \+ Spares



Core Optics Issues

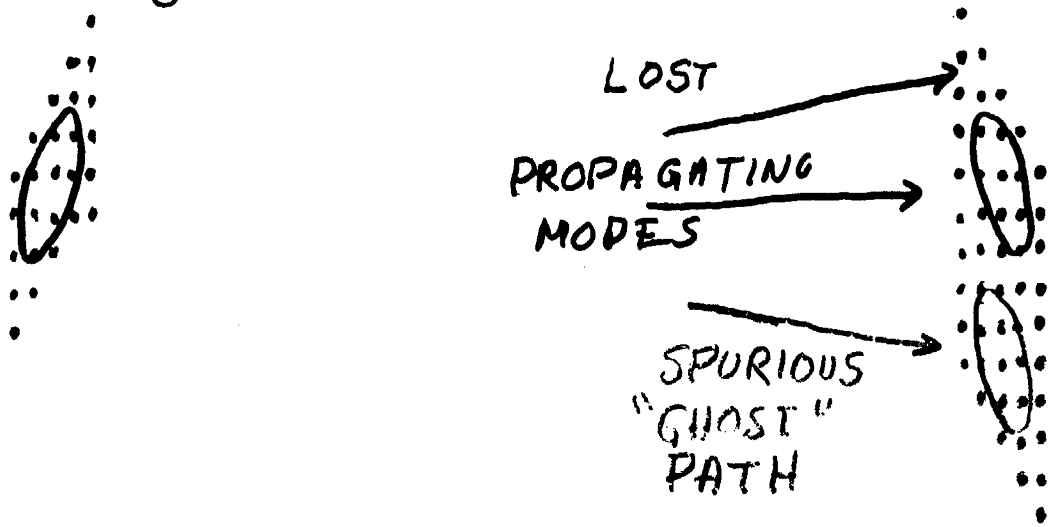
- Optical surface imperfections
  - ›› Radius of curvature: Relative and absolute accuracies
  - ›› Surface figure errors: Low spatial frequency errors leading to small angle scattering
  - ›› Microroughness: High spatial frequency imperfections leading to large angle scatter
- Absorption
  - ›› Coatings
  - ›› Substrates
- Thermal Noise
  - ›› High mechanical Q to minimize thermal noise ($Q \sim 10^6$-10^8)
  - ›› Size, density, speed of sound,...

Evaluating Optics Performance

- Primary tool is computer model of full recycled interferometer
    - FFT-based optical propagation code
    - Includes the surface figure of all optical components (either real or simulated)
    - Includes OPD of substrates
    - Solves for carrier and sidebands for modulation/demodulation
- Contributions from many people
    - Original code courtesy of Jean-Yves Vinet and Patrice Hello (VIRGO)
    - Extensive modification and enhancement by Partha Saha, Yaron Hefetz, and Brett Bochner
    - Used to establish initial LIGO requirements by Bill Kells

FFT Interferometer Model

- Most studies performed with 35 cm x 35 cm window covered by 128 x 128 grid



- Realistic accounting of of small angle scatter out to

$$\theta \approx \lambda/(\Delta x) \approx 0.4\,\mathrm{mrad}$$

- Larger angle scatter taken into account with overall loss term

Initial Core Optics Requirements

- Tight matching of all optical parameters arm to arm

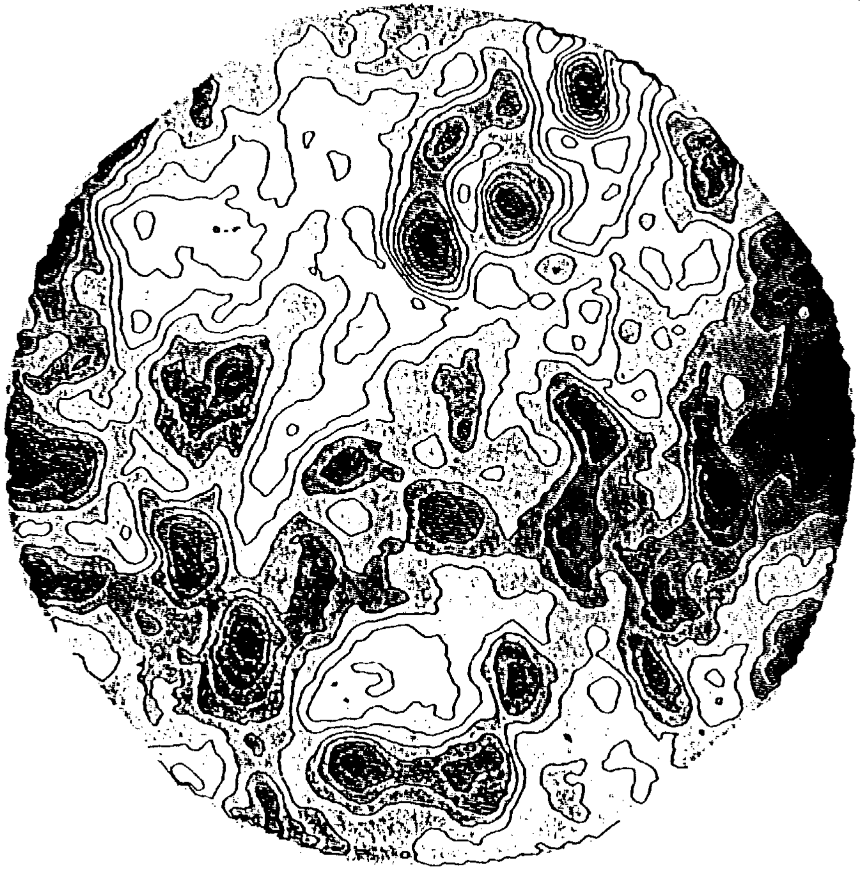
Physical Quantity	*Test Mass*		*Beam splitter*	*Recycling mirror*
	End	*Input*		
Diameter of substrate, ϕ_s (cm)	25	25	25	25
Substrate Thickness, d_s (cm)	10	10	4	10
1 ppm intensity contour diameter (cm)	24	19.1	30.2[a]	19.2
Lowest internal mode frequency (kHz)	6.79	6.79	3.58	6.79
Mass of Suspended Component (kg)	10.7	10.7	6.2	10.7
Nominal surface 1 radius of curvature (m) and g_i factor	7400 g_2=.46	14540 g_1=.725	∞	9890 g=.9984
Tolerance on radius of curvature (m)	absolute: +220 matching: ±111	-1000, +145	>-720 km convex, >200 km concave	-100, +500

[a] For these 45° angle of incidence optics, this is the smallest diameter circle centered on the optic face which is everywhere outside of the 1 ppm intensity field.

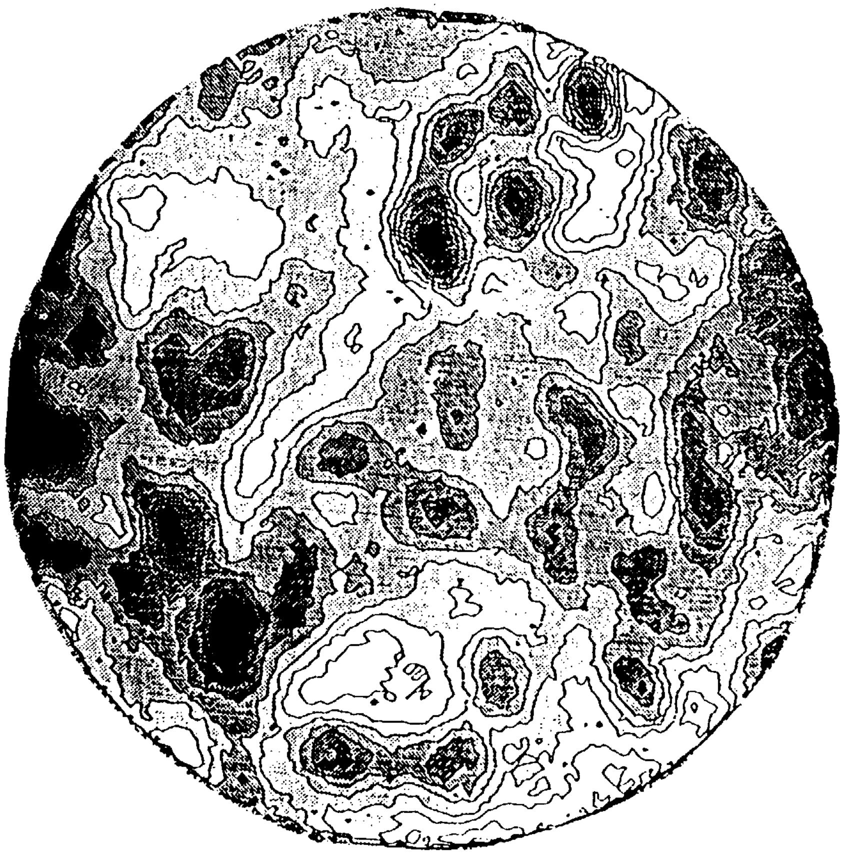
Core Optics-Polishing

- Conclusion: rms deviation from sphere < 1nm over 20cm diameter are achievable!
  - ›› In some cases, apparent rms ~0.5 nm measured
- With care, measurements at ≤ 1 nm level possible
  - ›› Reproducible features seen; Consistent intercomparisons demonstrated
  - ›› Small, subtle systematic effects noticed
    - **Flat reference vs. curved surface**
    - **Fizeau path differences**
    - **Focus effects**

CONTOUR INTERVAL ~ 1 NANOMETER
SERIAL NUMBER 001

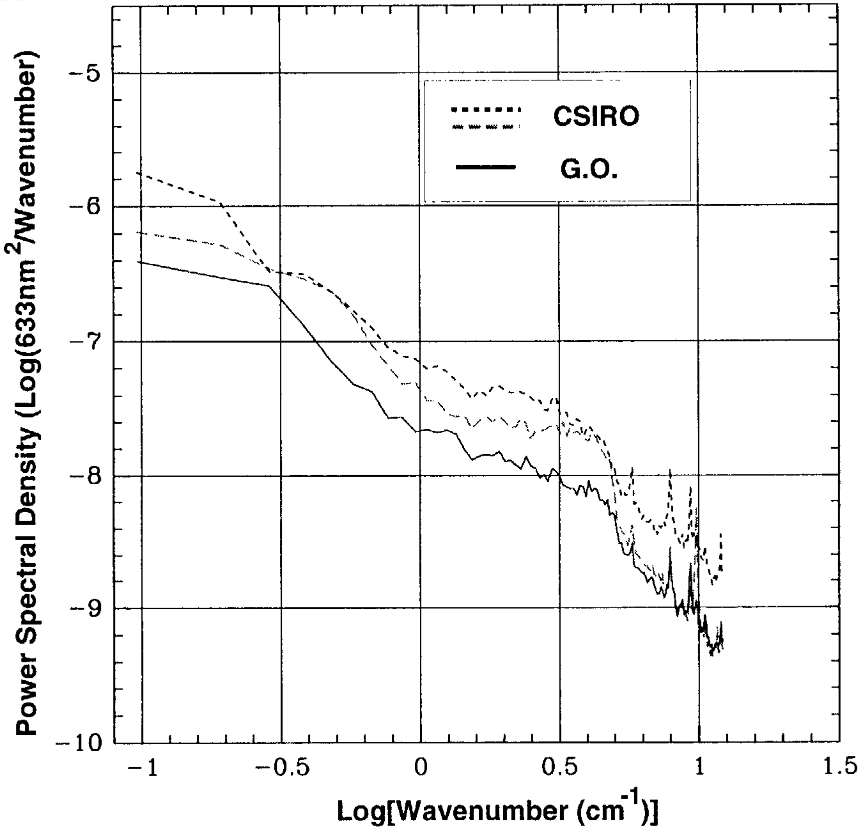


HDOS MEASUREMENT
(1.58 nm RMS)



NIST MEASUREMENT
(1.75 nm RMS)

Surface Figure Errors



- NIST Measurements

Limit of FFT Simulation

CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

Microroughness/Large Angle Scatter

- Largest source of lost optical power in initial detectors
- Industry definition of microroughness is typically tied to measurement instrument
  - LIGO “definition” includes spatial frequencies 4.3-7500 cm^{-1}
- For simple “smooth” surfaces,

$$\text{Scatter Loss} = \left(4\pi\frac{\sigma}{\lambda}\right)^2$$

  - For $\lambda = 1.063\mu\text{m}$, $\sigma = 0.2\text{nm}$, scatter loss ~ 6 ppm
- Point defects cause few ppb loss each
- Conventional wisdom says that substrate roughness dominates over coating nonuniformity at high spatial frequencies

Pathfinder Microroughness Results

- Comparative surface roughness measurements made at REO

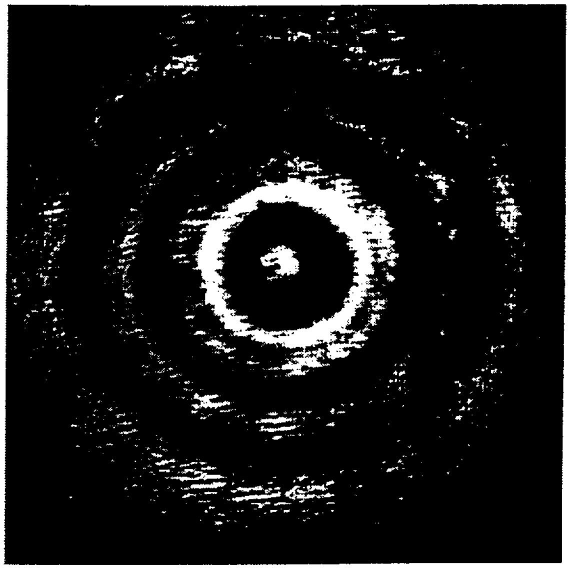
Polisher	Optic/Surface	Microroughness (Å rms)	
		Micromap SW (5 location ave.)	PSD area analysis (R. Weiss)
CSIRO	006/Curved	3.6	3.7
	006/Flat	2.8	2.7
GO	005/Curved	0.85	0.6 - 1.4
	005/Flat	0.88	0.7 - 1.2

- CSIRO microroughness improved to 1-2 Å in initial LIGO production

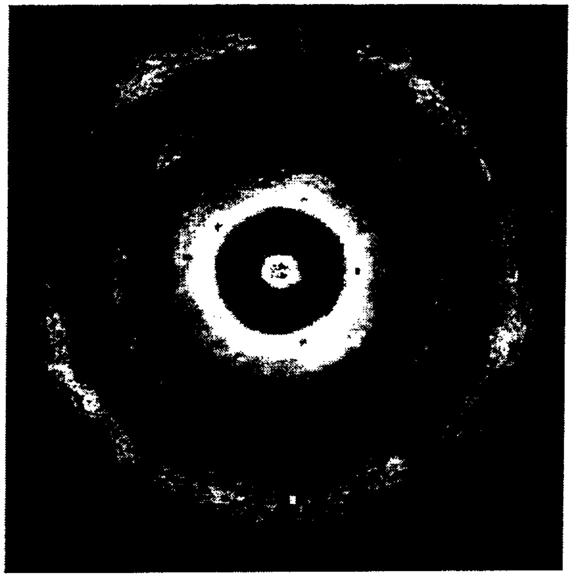
Coating Uniformity Development

- Coating Uniformity Development: REO
  - Goal: Scale up low loss ion beam sputtered coating technology to LIGO diameters
  - Preliminary test pieces show good uniformity to 15 cm diameter
  - Final verification: Coat Pathfinder optics for 633 nm and test
- Development of new test technique
  - Measurements: Doug Jungwirth, Alex Golovitser
  - Analysis: Hiro Yamamoto, Bill Kells
  - Coatings: Research Electro Optics, Ramin Lalezari, Dale Ness
- Conclusion: Large-scale uniformity at 0.5 nm level is possible with current technology

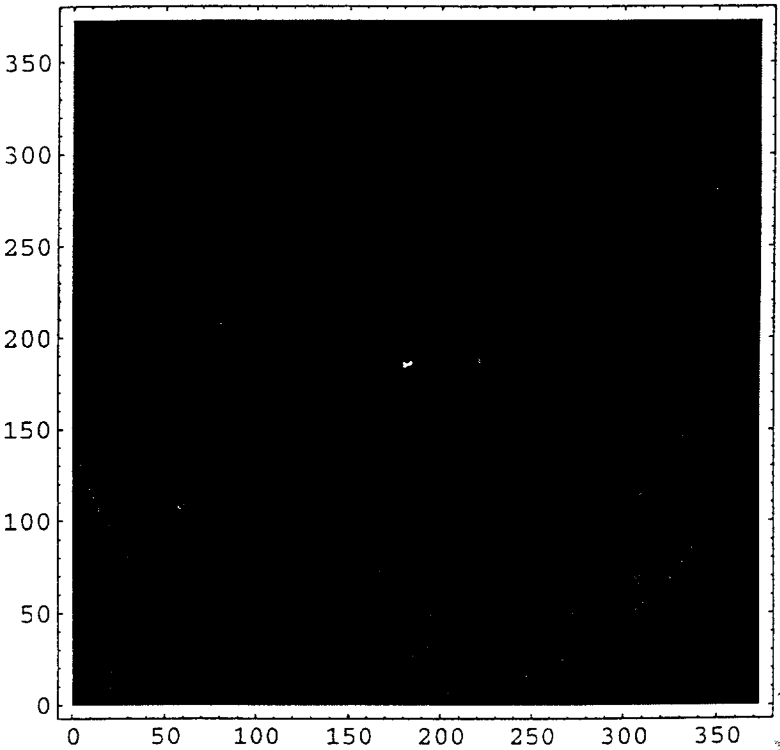
Uncoated



Coated



Difference



~0.6 nm (RMS)

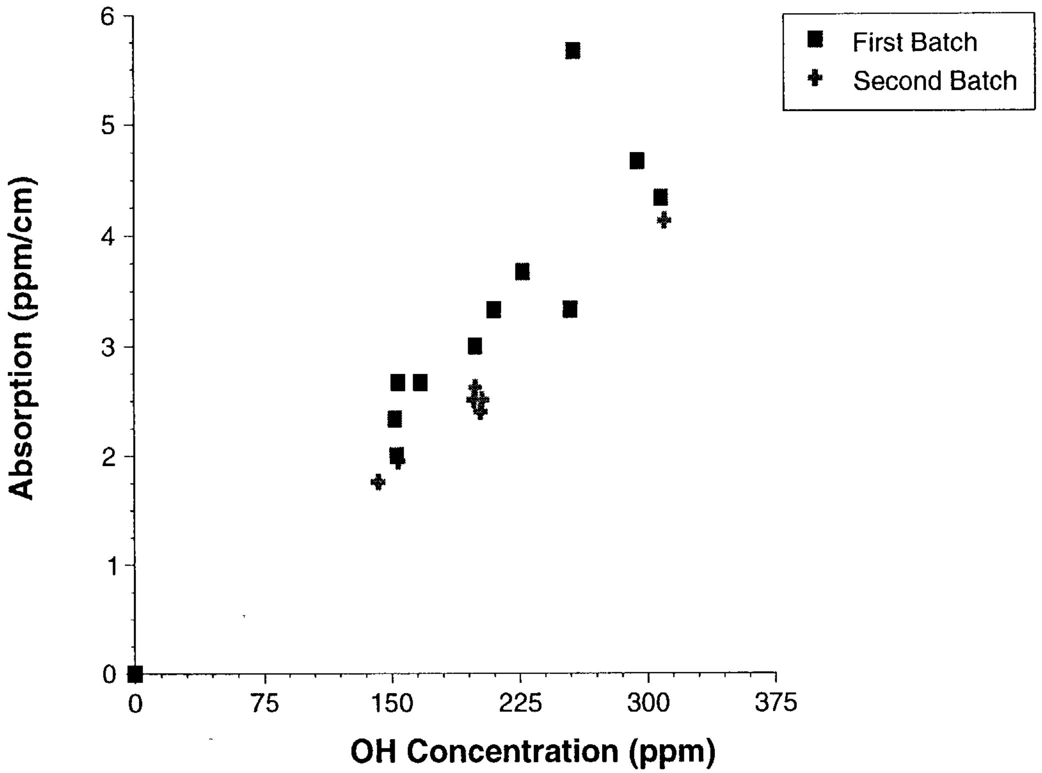
Absorption Effects

- Surface distortion
  - Important for reflective and transmissive optics
  - Typically not important in SiO_2 due to low expansion coefficient
- Thermal lensing
  - Important for transmissive optics only
  - Important in SiO_2 due to low thermal conductivity and high dn/dT
- Heat deposition matches beam profile; temperature gradient from heat flow to optic surfaces (radiatively coupled to vacuum chamber)
  - First order distortion is a simple change in radius (or simple lens)
  - Gaussian beam profile leads to higher order distortions

Absorption Sources

- Coatings
  - Source of absorption unknown
  - IR values (typically?) 0.5 ppm
- Substrates: SiO_2
  - IR absorption due to OH (usually?)
    - **Typically 2-20 ppm/cm**
  - Shorter wavelength absorption due to metallic impurities (?)
    - **Typical value at 514 nm ~ 2 ppm/cm (?)**
- Substrates: Sapphire
  - Source of absorption unknown
  - IR values range from 3-1000 ppm/cm

Absorption in SiO_2



Future Directions

- Polishing
  - ›› Surface figure improvements (factor 5?)
- Coatings
  - ›› Higher uniformity, lower absorption (factor 10?)
- SiO_2 substrates
  - ›› Understand limits to Q (fundamental limit or technical limit)
  - ›› Reduced OH concentration (factor 10?)
  - ›› Larger sizes
- Sapphire substrates
  - ›› High Q, high density, high speed of sound desirable for thermal noise
  - ›› High thermal conductivity good for thermal lensing
  - ›› Problems: optical figure, birefringence, homogeneity, absorption,....

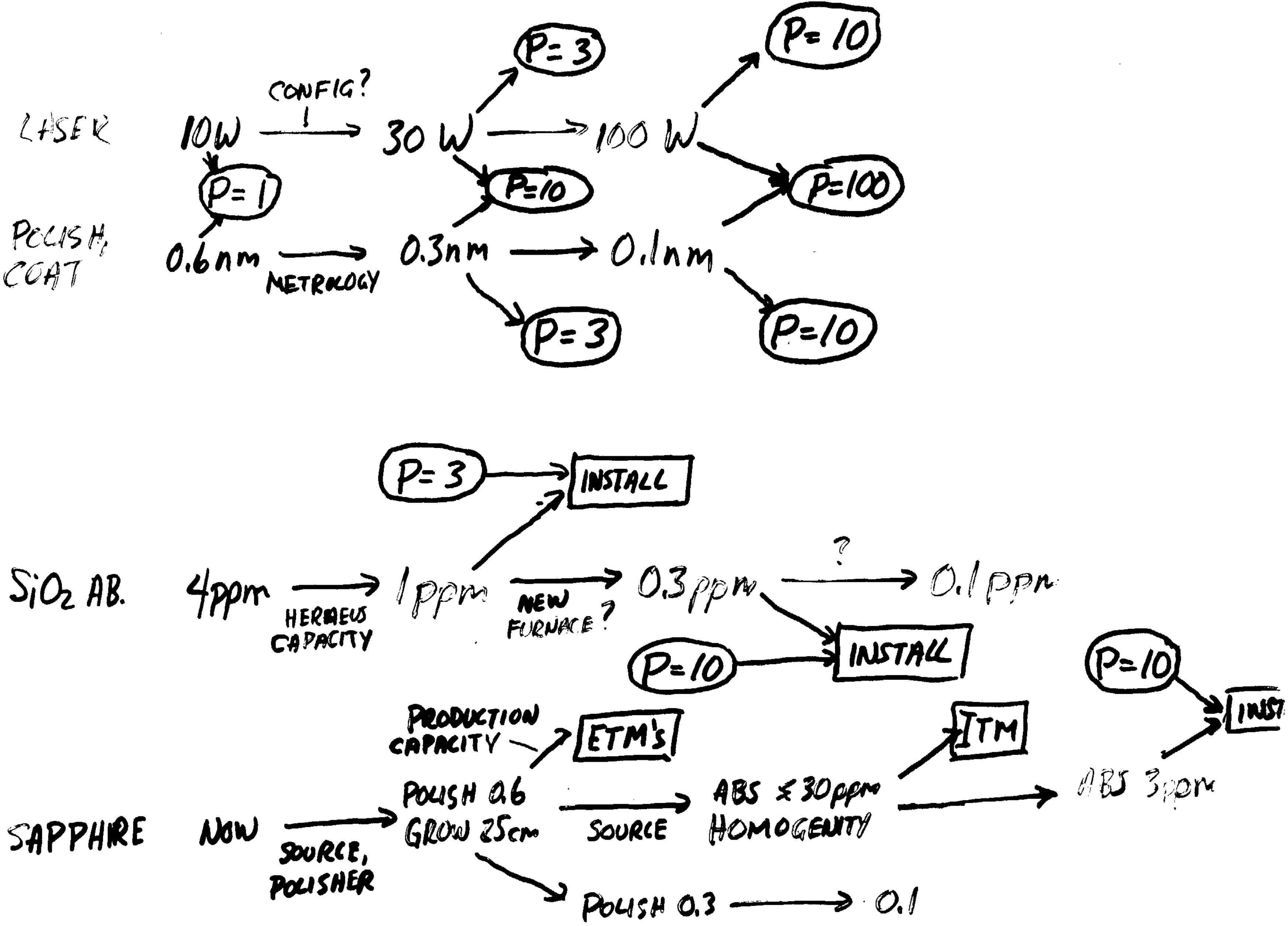
FFT Interferometer Model

- Most studies performed with 35 cm x 35 cm window covered by 128 x 128 grid

- Realistic accounting of of small angle scatter out to

$$\theta \approx \lambda/(\Delta x) \approx 0.4 \mathrm{mrad}$$

- Larger angle scatter taken into account with overall loss term


LASER
10W
CONFIG?
30 W
100 W
P= 3
P= 10
P=1
P=10
P=100
POLISH, COAT
0.6nm
METROLOGY
0.3nm
0.1nm
P= 3
P=10
P= 3
INSTALL
SiO2 AB.
4ppm
HERAEUS CAPACITY
1ppm
NEW FURNACE?
0.3ppm
?
0.1ppm
P=10
INSTALL
P=10
INST
PRODUCTION CAPACITY
ETM's
ITM
SAPPHIRE
NOW
SOURCE, POLISHER
POLISH 0.6
GROW 25cm
SOURCE
ABS ≤ 30ppm
HOMOGENITY
ABS 3ppm
POLISH 0.3
0.1

[redacted]

LIGO PhotoDetectors & Testing

- Overview and Requirements

  — detect the modulated output beam intensities corresponding to length and frequency changes in the interferometer.

  — integrated with ASC Wavefront Sensing equipment on external ISC platforms located in the LVEA

  ›› PD Power Requirements and basic design features

  — Dark Port: 600mW continuous power

  — QE ~ 80% at 1064nm ==> InGaAs

  — Transient Power: ~2Joules in ~~1~~ 10msec

  ›› RF modulation Frequencies

IFO	FSR_{MC} (MHz)	f_R (MHz)
WA, LA 4 km	12.231	24.463
WA 2 km	9.816	29.449

where FSR_{MC} is the mode cleaner free spectral range; f_R = Resonant Sideband frequency. Frequencies for the nonresonant sidebands f_{NR} must be approximately an integer multiple of the mode cleaner free spectral range FSR_{MC}.

  ›› small backscatter

  ›› low contamination from electronic or thermal noise

PD Signal-to-Noise Calculations

Shot noise in the detected antisymmetric port photocurrent = 10 times < than the total electronic noise of the PD assembly. Includes both thermal (Johnson) noise and amplifier noise contributions. For an individual PD + amplifier:

$$V_{SN} = Z_D\sqrt{2e(I_{DC}/N)}\sqrt{\frac{3+P_C/P_{SB}}{2+P_C/P_{SB}}} \geq 10V_{EL} \qquad (1)$$

V_{SN} is the shot noise voltage equivalent in **one PD**

Z_D is the equivalent resistance of the individual PD circuit at resonance

e is the electron charge

I_{DC} is the **total** DC current in all the PD at a given light intensity

P_C is the carrier power

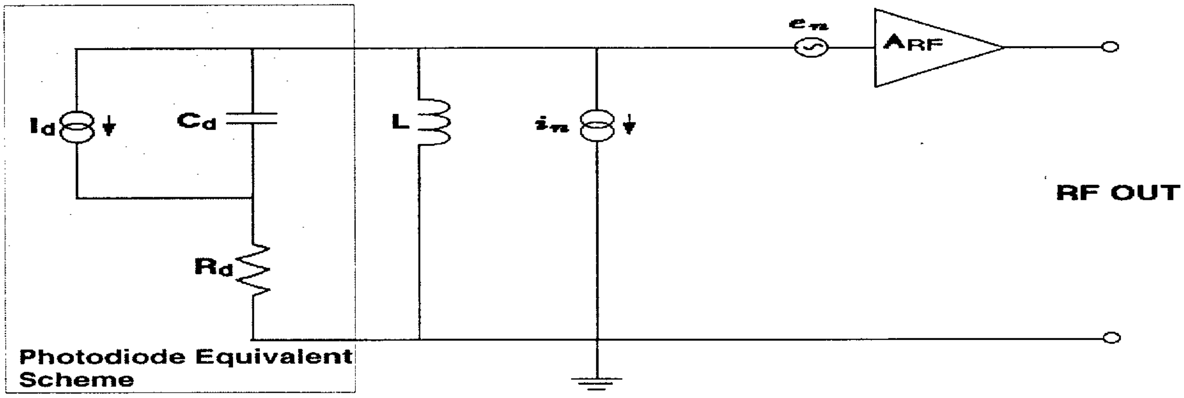
P_{SB} is the side band power. (For our calculations, $P_c/P_{SB} = 1/2$)

N is the number of channels (PD)

V_{EL} is the *electrical noise of each channel.* Its consists of the quadratic sum of the equivalent thermal noise of the PD impedance Z_D and the amplifier noise V_{AMP} (max 2mV): $V_{EL}^2 = \sqrt{4k_BTZ_D}^2 + (V_{AMP})^2$

k_B is the Boltzman constant,

T is the temperature in degree Kelvin.



For tuned circuits, at resonant frequency: $Z_D = \dfrac{1}{R_D(\omega_0 C_D)^2}$

Experimental Test set-up

Figure 1 presents the optical setup used for our PD evaluations. The laser is a Lightwave 126 laser, with maximum power of about 800mW.

Experimental Setup

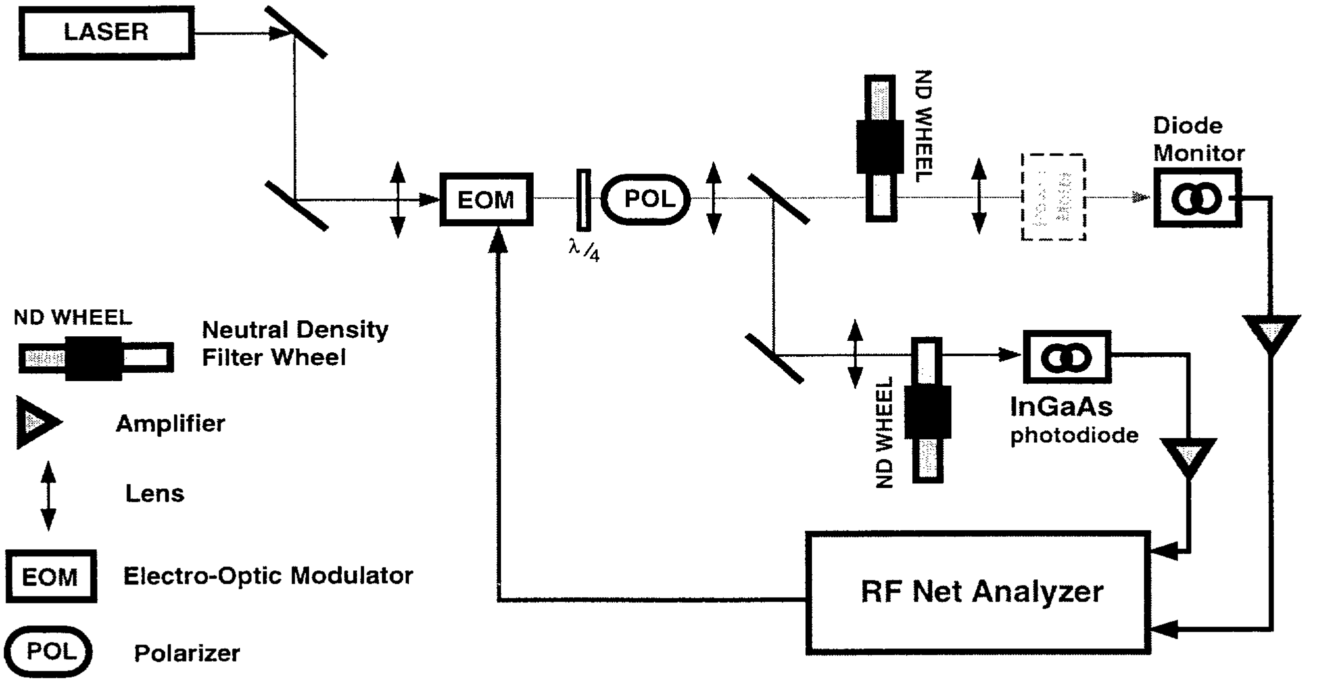


Figure 1: Experimental setup for PD evaluation

PD Electrical Properties (1)

›› Photodiode C and R in dark

Typical Capacitance and Serial Resistance at 10V reverse Bias Voltage

Brand	**Type (Diameter)**	**Cd**	**Rd**
Hamamatsu	G5832-1 (1mm)	68 pF	12.8 Ω
	G5832-2 (2mm)	250 pF	8 Ω
	G5832-3 (3mm)	500 pF	8.8 Ω
	***G5114-3** (VIRGO)*	***330 pF***	***12** Ω*
EG&G Canada	C30642G (2mm)	72 pf	9Ω
	C30665G (3mm)	200 pF	6 Ω
GPD 2mm	GAP2000 (2mm)	122pF	9 Ω
	GAP600 **Ge**	*60 pF*	*10* Ω

››PD to PD variation: 2mm Ham: 20%; EG&G <15%.

››Reverse Bias Voltage effects on PD Characteristics

InGaAs PD Capacitance and Resistance at various Bias Voltages (average values)

Brand, Diam. & type of PDs	**Parameter---->**	**Cd in pF**			**Rd in Ω**		
	Bias Volt.(V)-->	**1**	**5**	**10**	**1**	**5**	**10**
Hamamatsu	3mm G5832-3	1020	615	500	8.5	8.6	8.8
Hamamatsu	2mm G5832-2	560	300	248	8	8	8
E G & G	2mm C30642G	140	85	70	9	9	9
E G & G	3mm C30665G	500	250	200	6	6	6
G P D	2mm GAP2000	177	135	122	9.2	9.2	9.2

PD Electrical Properties (2)

››Photodiode C and R Variation with the Incident Light Power

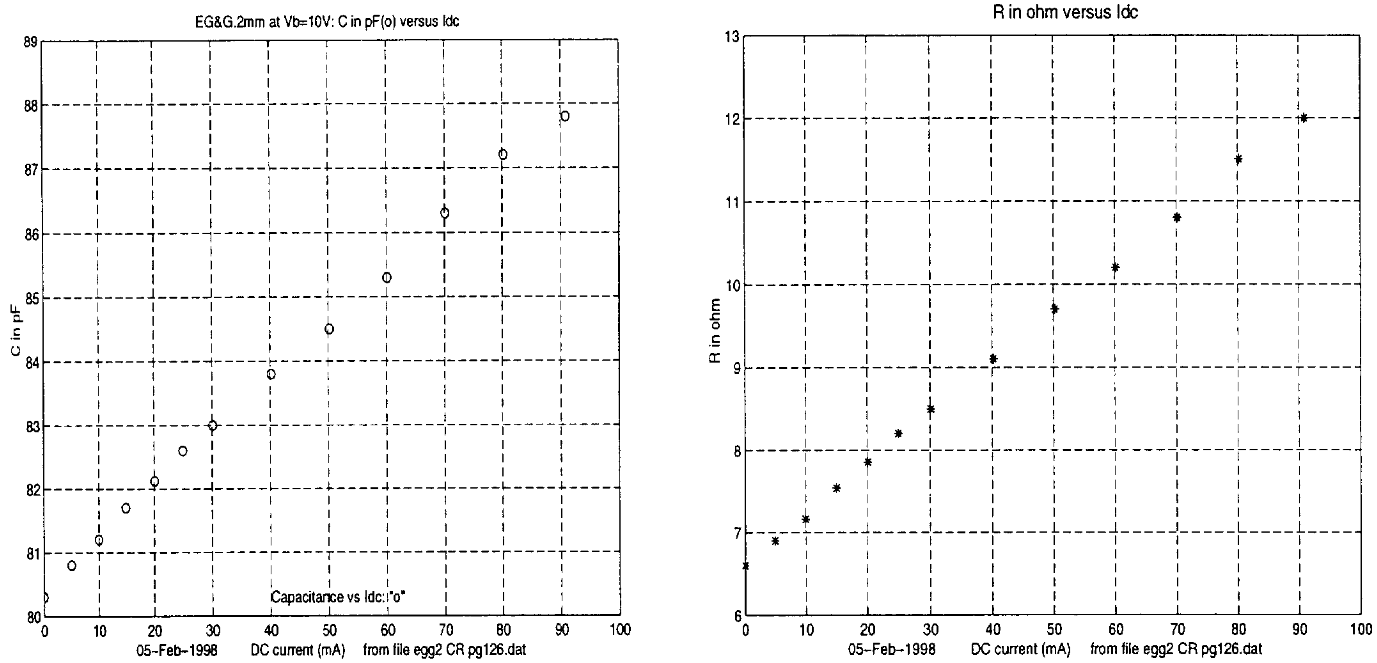


Figure 2: EG&G 2mm: C and R dependence on the light induced DC current

The C and R variation with the light level is due to two mechanisms:

- the light level itself, which is responsible of the amount of pairs electrons-hole produced in the junction, which affects directly the electrical properties of the PDs,
- change in junction temperature due to the power dissipation

PD Opto-Electrical Properties (1)

››Photodetector Spatial Uniformity.

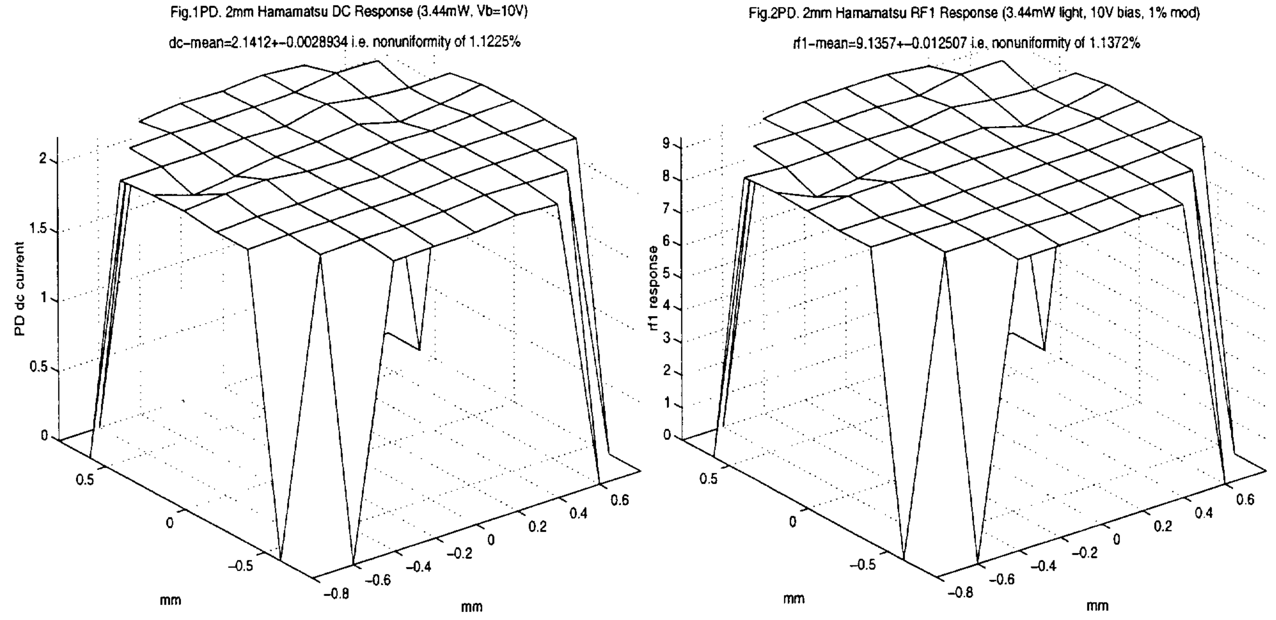


Fig.1PD. 2mm Hamamatsu DC Response (3.44mW, Vb=10V)
dc-mean=2.1412+-0.0028934 i.e. nonuniformity of 1.1225%

Fig.2PD. 2mm Hamamatsu RF1 Response (3.44mW light, 10V bias, 1% mod)
rf1-mean=9.1357+-0.012507 i.e. nonuniformity of 1.1372%

Figure 3: DC(left) and RF(right) spatial uniformity of the G5832-2 PD

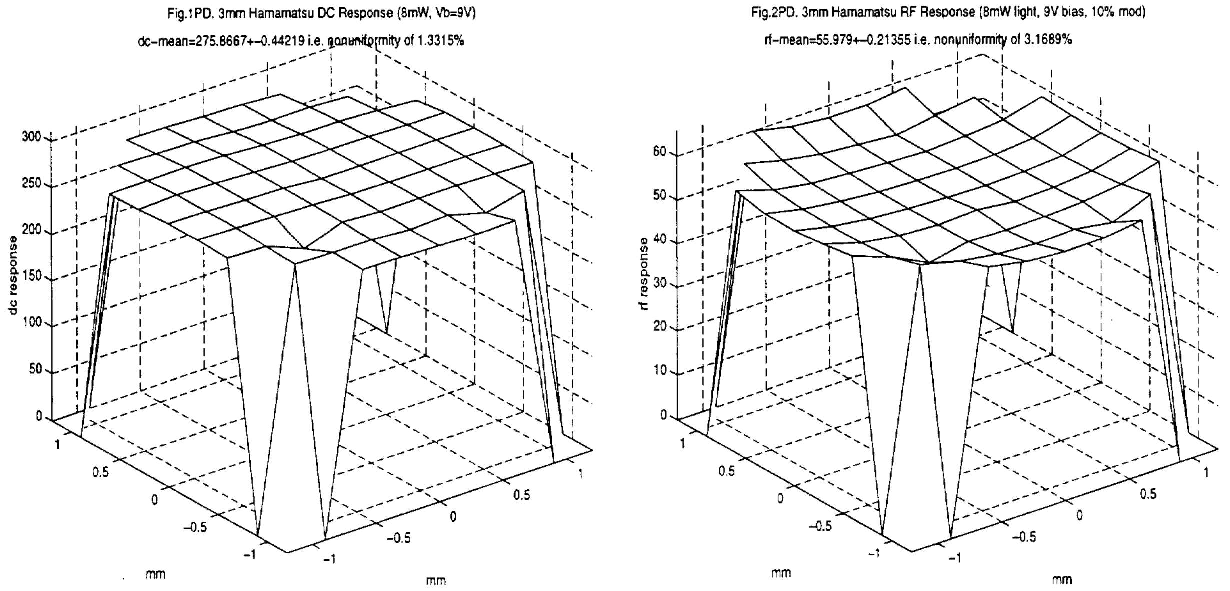


Fig.1PD. 3mm Hamamatsu DC Response (8mW, Vb=9V)
dc-mean=275.8667+-0.44219 i.e. nonuniformity of 1.3315%

Fig.2PD. 3mm Hamamatsu RF Response (8mW light, 9V bias, 10% mod)
rf-mean=55.979+-0.21355 i.e. nonuniformity of 3.1689%

Figure 4: DC(left) and RF(right) spatial uniformity of the G5832-3 PD

PD Opto-Electrical Properties (2)

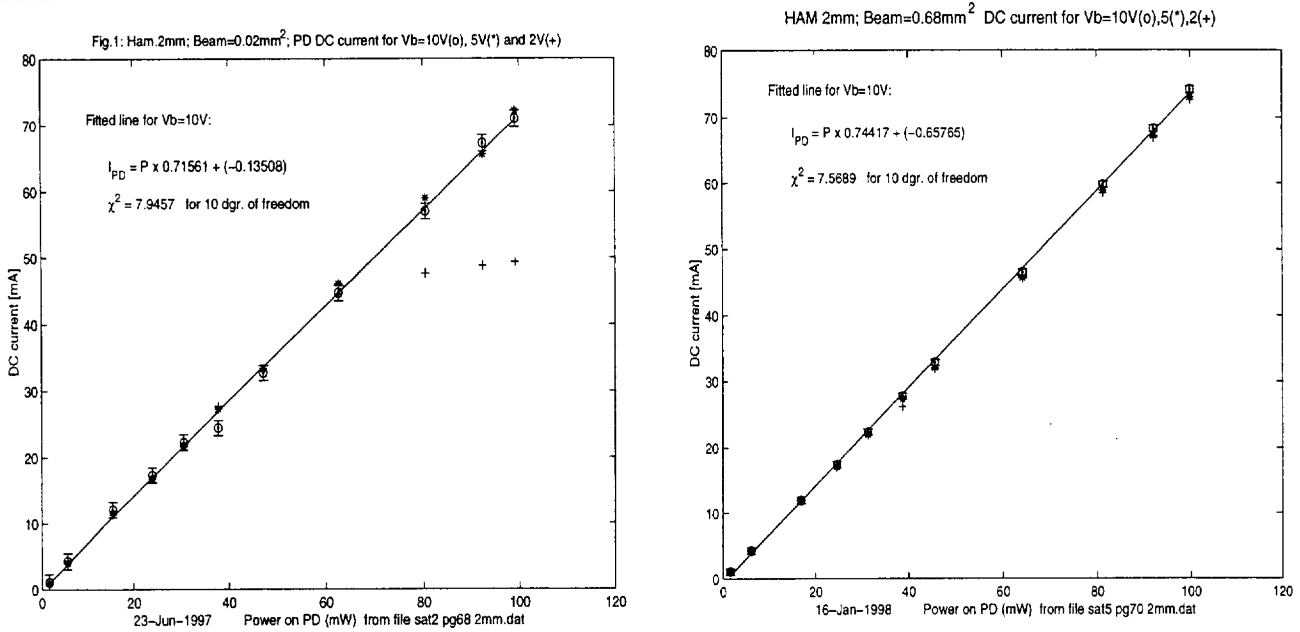


Figure 5: DC response of G5832-2 at various bias Voltages and Beam sizes. Modulation 1%

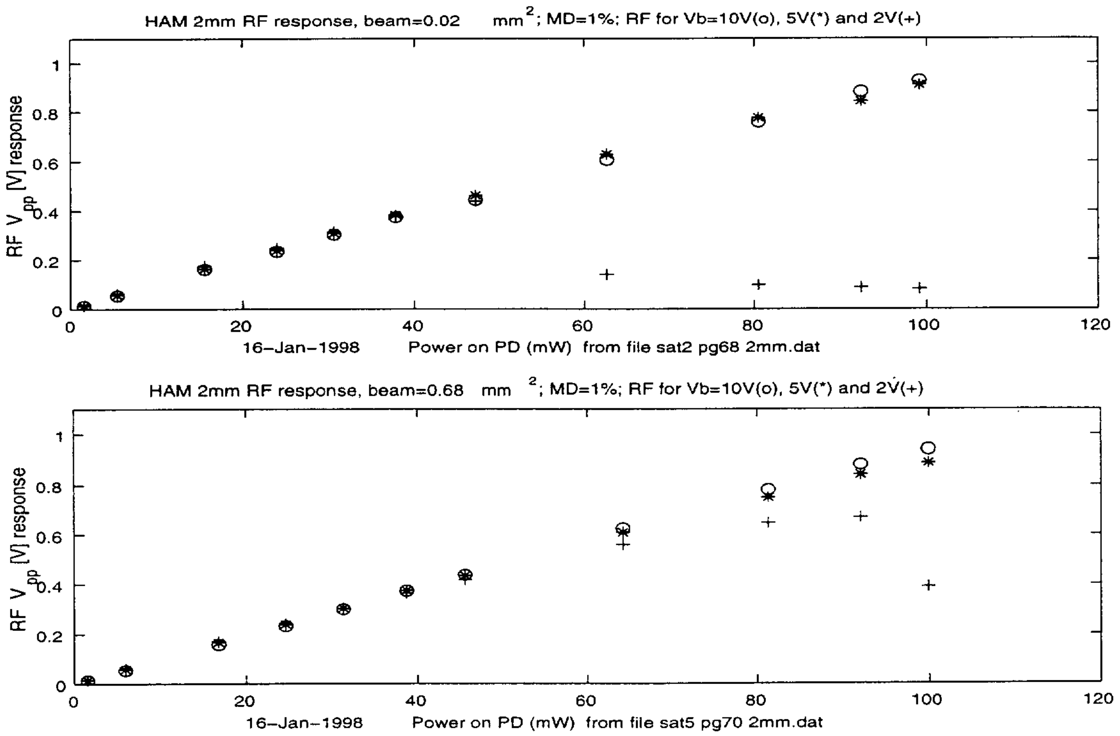


Figure 6: RF response of G5832-2 at various bias Voltages and Beam sizes. Mod 1%

PD Opto-Electrical Properties (3)

Summary for Figure 5 and Figure 6

››DC and RF response dependence on the Bias Voltage

– as the bias voltage increase, the PD response is better at higher powers.

››Dependence on Beam Size (Energy Density)

– the higher the energy density of the beam is, the higher bias voltage is necessary in order to avoid the saturation. This effect push for a larger diameter diode. For the 3mm PD, the data are similar.

››Dependence on Modulation Depth

– Amplitude modulation depth up to 10% was studied.

– The equivalent LIGO modulation depth at the main modulation frequency is equivalent to 0.1–0.2% amplitude modulation depth.

– The saturation of the PD response occurs at lower power levels for higher modulation depth.

– LIGO ===> small modulation ==> data below are at MD=0.2%

PD Opto-Electrical Properties (4)

››DC Response of the PDs at Various Power Levels and QE

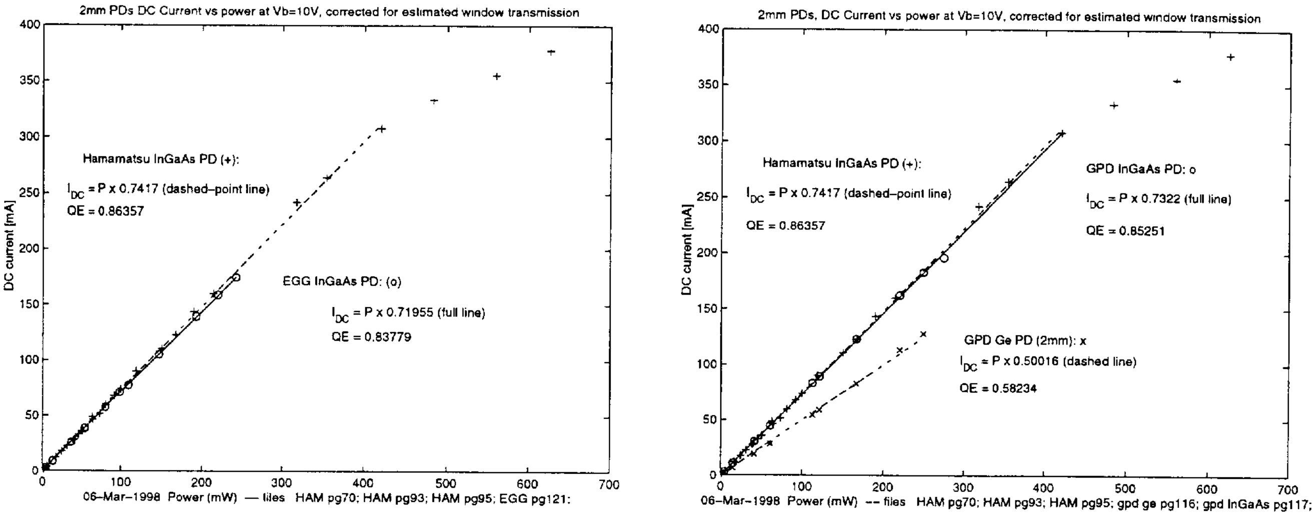


Figure 7: 2mm PDs: DC response of EG&G and HAM (left); GPD and HAM (right)

- *The DC response of the 2mm HAM PD is linear up to~450mW,.*
- without cooling, for the HAM 2mm PD we observed that after the exposure at high power (about 700mW), the capacitance and serial resistance were unchanged while the dark current increased by a factor of more than 100.
- The EG&G 3mm PD, with cooling, showed that the maximum DC current which can be handled by this detector is around 200mA.
- Up to about 200mW, the estimated QE for InGaAs PDs without window are: 86% (HAM), 85% (GPD) and 84% (EG&G). The Ge PD has a significant lower QE (58%). Errors > 5%.

The QE = ratio between the number of PE created/ number of incident photons. In terms of "*responsivity*" or "*radiant sensitivity*" S (photoelectric current/incident radiant power at a given wavelength $\lambda[\mathrm{nm}]$, in units of A/W), we may write:

$$\mathrm{QE} = \frac{S[\mathrm{A/W}] \cdot 1240}{\lambda[\mathrm{nm}]} \times 100\,\% \qquad (2)$$

PD Opto-Electrical Properties (5)

››RF Response at Various Power Levels

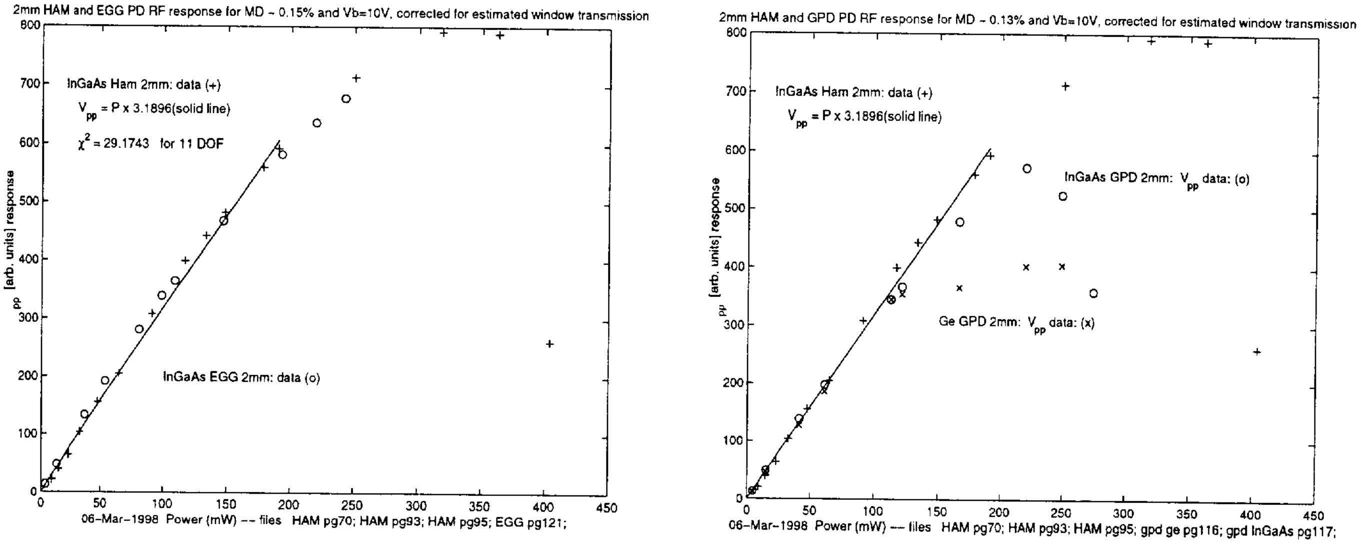


Figure 8: 2mmPD: RF response of EG&G and HAM (left); GPD and HAM (right)

— *the RF response is linear till about 200mW for HAM and EG&G.* Note that the GPD starts to saturate earlier, while Ge GPD is the worst.

EG&G 3mm PD performed similar to the 2mm.

››Maximum Continuous Power Capability

— 2 weeks @175mA (HAM) and @135mA (EG&G) with cooling =========> no change in characteristics

››Transient Peak Power Capability (work in progress)

— With a current limiter @200mA, HAM 2mm can support 700mW for about 1 sec without damages.

— above 200mA the EG&G diode with bias voltage on, is damaged irreversible.

Optimized RF Transimpedance

and minimum DC current per device to fulfill LIGO SNR requirements (see Section B.1. of [LSC PDD])[a]. *10V Bias voltages is assumed*

Description	Z[Ω]@ 25MHz, 10Vbias	I_{PD}^{min} mA	# PD req	Power / PD [mW]	Central Intensity[b] mW/mm^2	DC Current /PD [mA]
HAM G5832-1 (1mm)	682	6	8	75	765	57
HAM G5832-2 (2mm)	81	95	4	150	382	114
HAM G5832-3 (3mm)[c]	18	100	>19	N/A	N/A	N/A
HAM G5114-3[d]	*31*	*454*	*1*	*600*	*678*	*456*
EG&G C30642G 2mm	633	7	4	150	382	114
EG&G C30665G 3mm	169	33	4	150	170	114
GPD GAP2000 2mm[e]	302	16	4	150	382	114

a. See page 2 for impedance and current calculation formulae

b. Assuming 1/e^2 beam diameter is chosen to be half the physical diameter of the diode; this is conservative from the standpoint of collection efficiency, but may be necessary to reduce backscattering from the device edges.

c. The RF impedance of the stock 3 mm diode is too low to realize LIGO SNR constraints (with room temperature electronics).

d. VIRGO custom diode (parameters communicated by R. Flaminio).

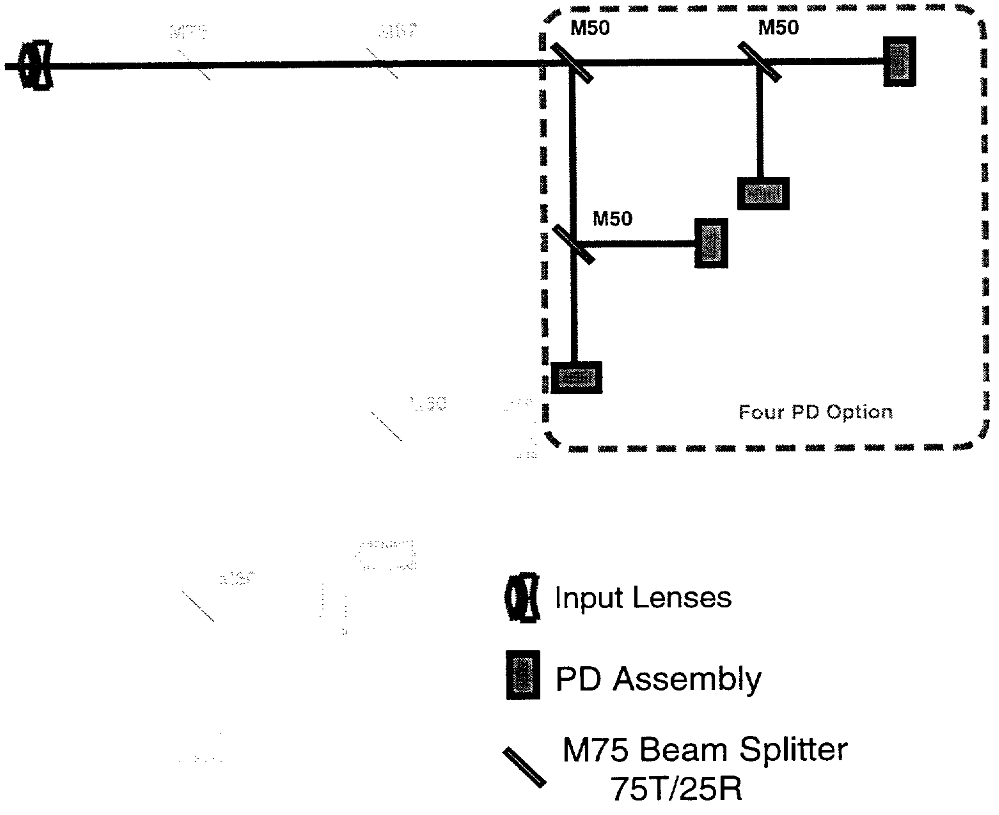
e. GPD Diode is marginally acceptable due to its RF response at high power.

I_{PD}^{min} represents the minimum PD DC current to fulfill the Signal to Noise requirement

Baseline PD Assembly Design

Figure 9 presents the PD assembly schematically. The design is proposed to be modular, to accommodate as many as 8 diodes and their optics and electronics. Total losses in optical components of about 5.3% are tolerable.

(3)



Photodiode Assembly

Figure 9: Photodiode Assembly Layout with full implementation (8 photodiodes). The 4-diode option is shown in the dashed box.

Note 1, Linda Turner, 04/21/98 09:23:16 AM
LIGO-G980049-29-M