Photodiodes for Initial and Advanced LIGO

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Outline

- Requirements (M. Zucker):

  What does LIGO want from a photodiode?

- Existing LIGO I devices Part I (A. Marin):

  Power handling, RF characteristics, spatial uniformity

- Existing LIGO I devices Part II (P. Csatorday):

  Thermal dissipation, surface reflectance, backscatter

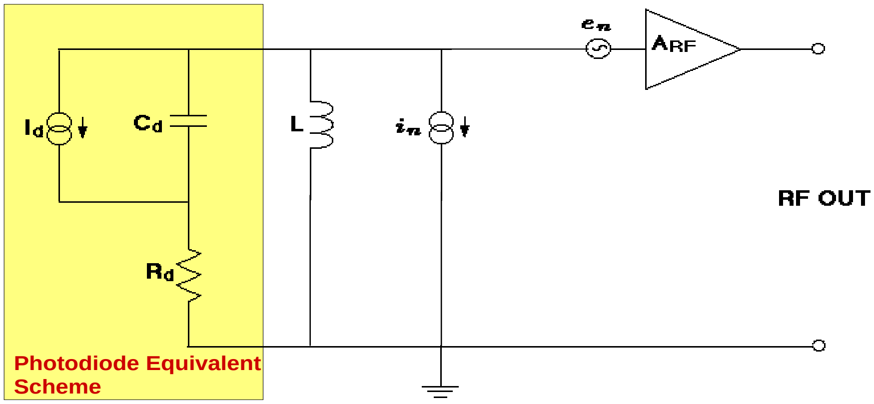
- Summary: Future directions for advanced LIGO

LIGO Photodetector Requirements

- Quantum efficiency
- SNR
- Linearity
- Spatial uniformity
- Backscatter
- Power handling: Steady-state
- Power handling: Transient

Front-End SNR

- LIGO I: f_0 = 25 - 32 MHz



- $10 < \frac{S_{shot}}{S_{elec}} \propto \frac{Z_D\sqrt{2eI_{DC}}}{e_n}$
- $Z_D = \frac{1}{R_D(\omega_0 C_D)^2}$
- need low R_D, C_D

- Both R_D and C_D depend on device area, which affects...
  - ››Power handling (at least in principle)
  - ››Backscatter (through area*solid angle conservation)

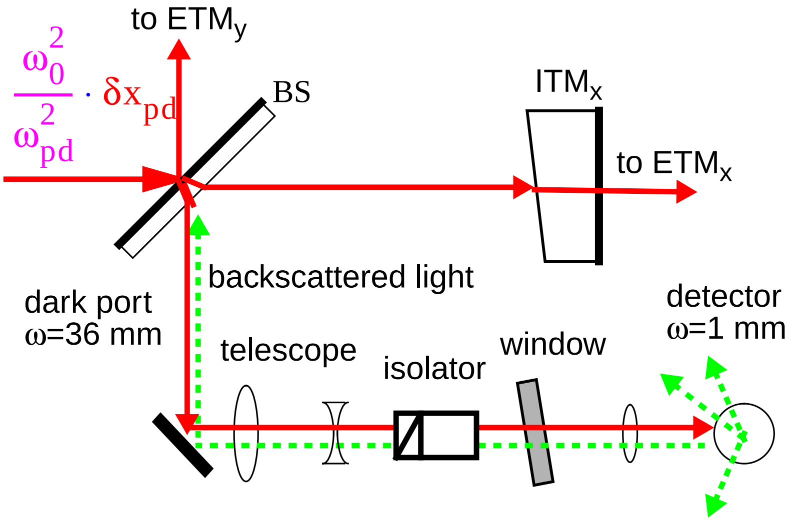
Linearity

- Gain compression at level which affects SNR (~ few dB ?)
- Noise: mechanisms poorly defined ; “zoo” of possible effects which might induce signals at f_0 , including
  - ››Two-tone intermodulation, $(2f_0 \;+/- f_{GW}) \times (2f_0 \;+/- f'_{GW})$
  - ››Hysteretic down conversion from $2f_0 - f_0 \times$ intensity fluctuation
  - ››???
- Need better models, testing with “realistic” photocurrent waveforms & noise sensitivities

Spatial Uniformity and Backscatter

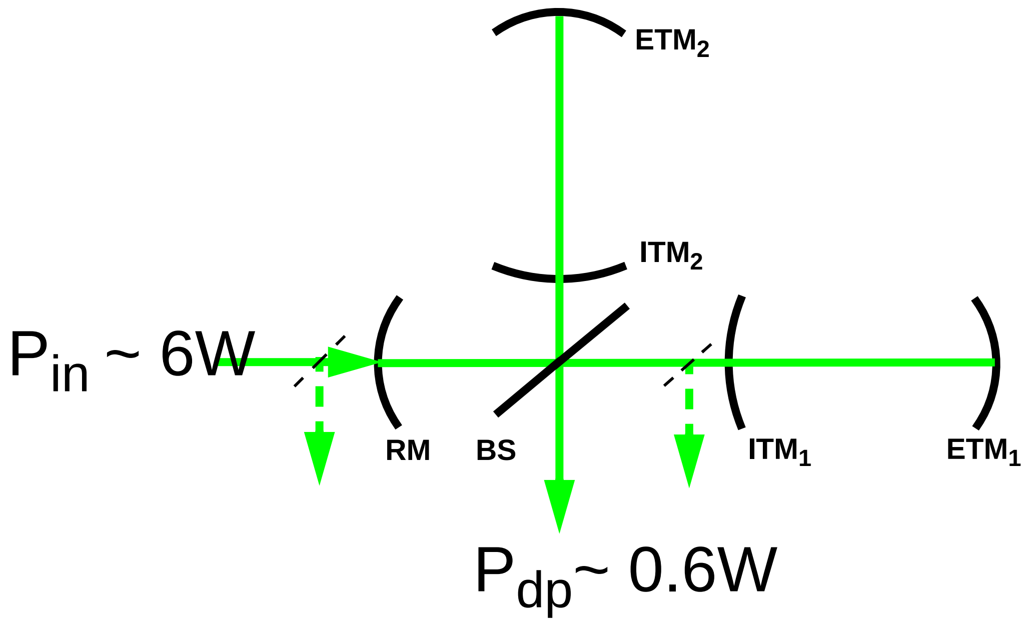
- Spatial uniformity:
  - ››Defeats modal orthogonality, enhancing effect of beam tube scattering recombination
  - ››Requirement can be relaxed with output mode cleaner
- PD Surface Backscatter

$$h_n^2 \sim P_{dp} \cdot BRDF \cdot \Delta\Omega \cdot \frac{\omega_0^2}{\omega_{pd}^2} \cdot \delta x_{pd}$$



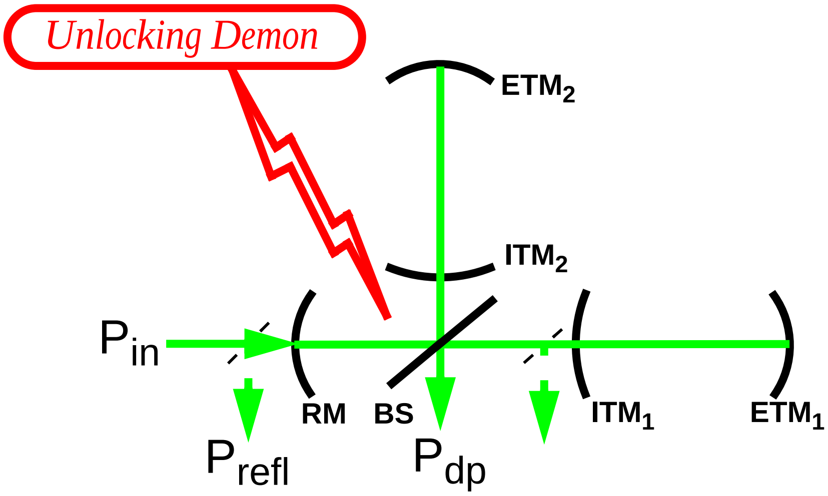
  - ››optical isolation (costs efficiency)
  - ››seismic /acoustic isolation (costs $)
  - ››improved BRDF
  - ››larger detector area

Power handling (steady-state)

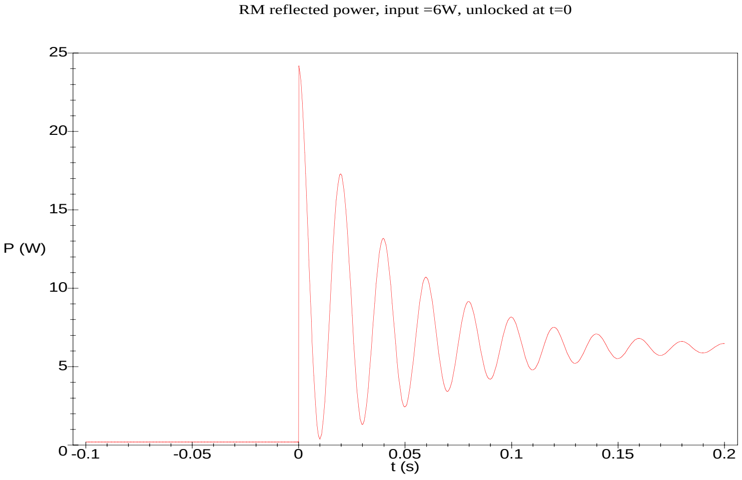


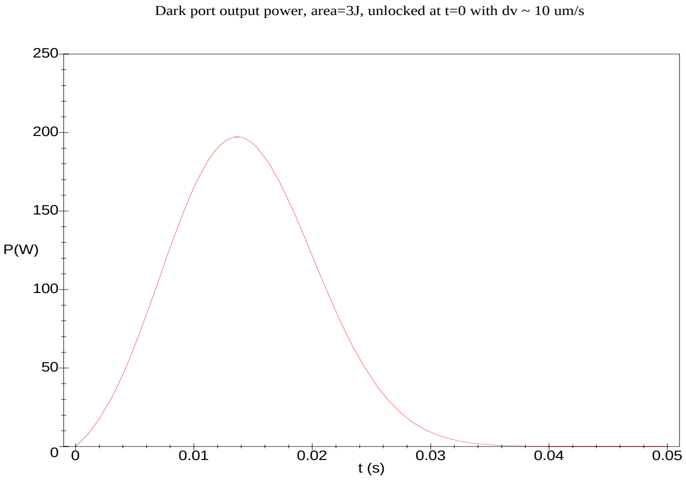
- $N_{pd} \geq P_{dp} / P_{MAX} \approx 4$; the fewer the better (SNR, $, scatter,...)
- tradeoff against linearity

Power handling (transient)



- Sudden loss of lock releases stored energy U~3J thru dark port
- P_{refl} rises briefly to 4 P_{in}
- EO shutter required (costs efficiency)


RM reflected power, input =6W, unlocked at t=0


Dark port output power, area=3J, unlocked at t=0 with dv ~ 10 um/s

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 1msec
  - ›› 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

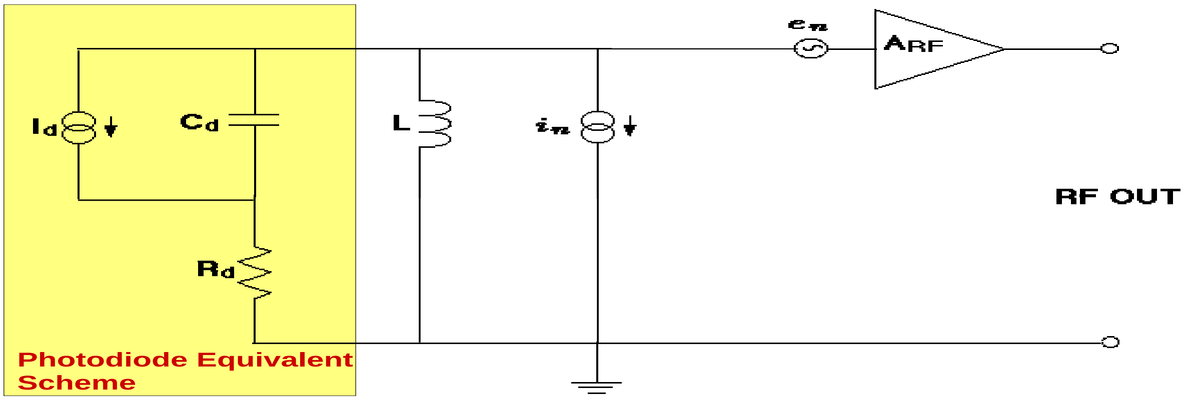
P_{SB} is the side band power. (For our calculations, $P_c/P_{SB} = 1/2$)

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

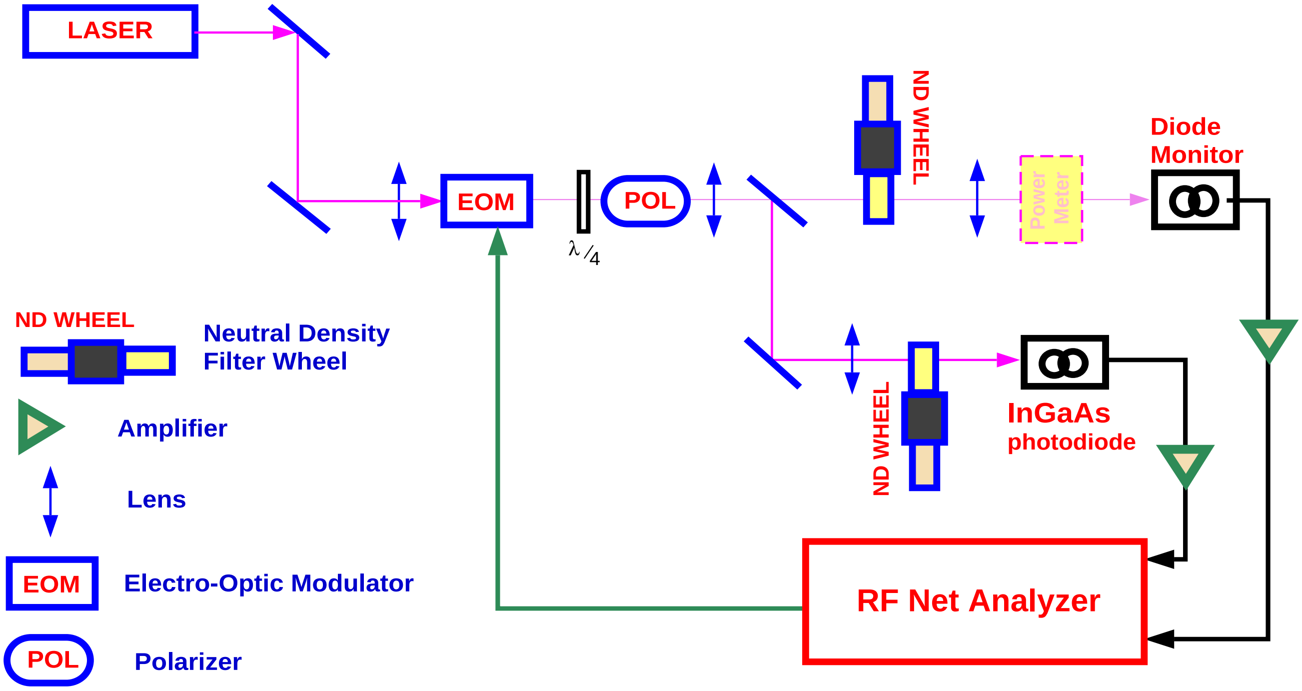


Figure 1: Experimental setup for PD evaluation

PD Electrical Properties (1)

›› Photodiode C and R in dark

Typical Capacitance and Serial Resistance at 10V reverse Bias Voltage

Brand	**Type (Diameter)**	**C_d**	**R_d**
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	GAP2000 (2mm)	122pF	9 Ω
2mm	*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.	**Parameter---->**	**C_d**	**in**	**pF**	**R_d**	**in**	**Ω**
& type of PDs	**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

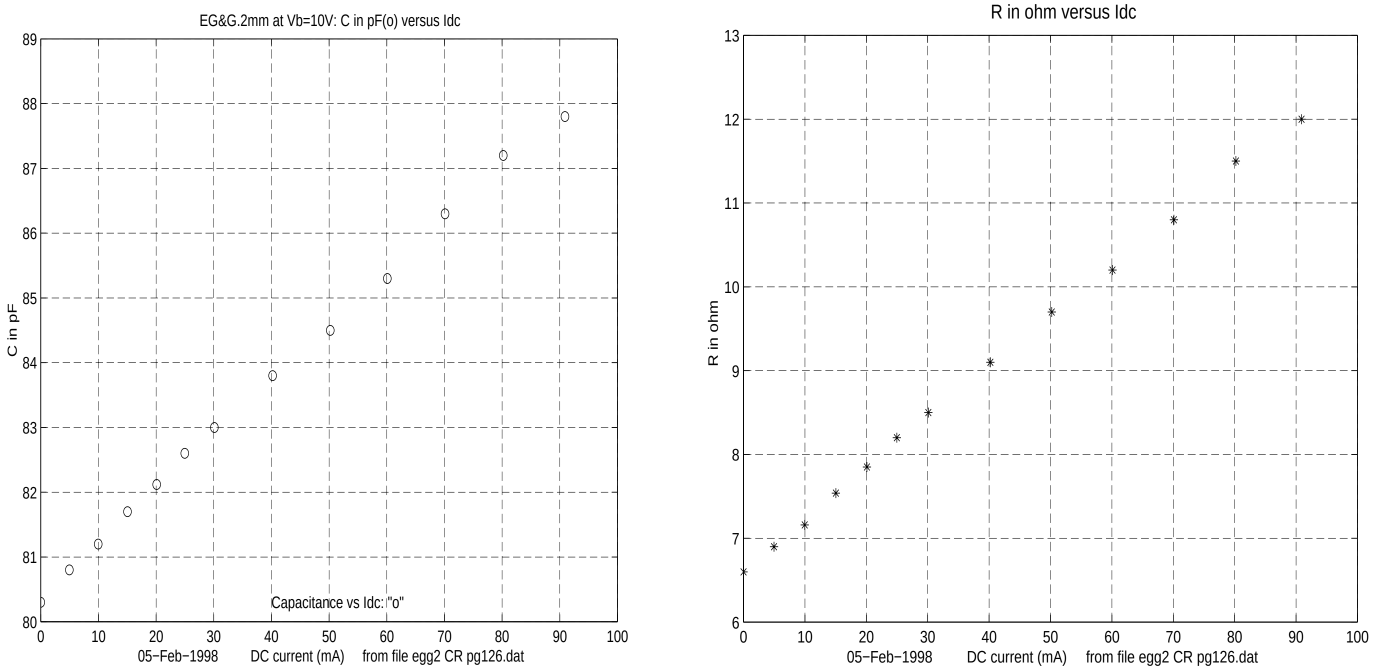


Figure 2: EG&G 2mm: C and R dependence on the light induced DC current

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.

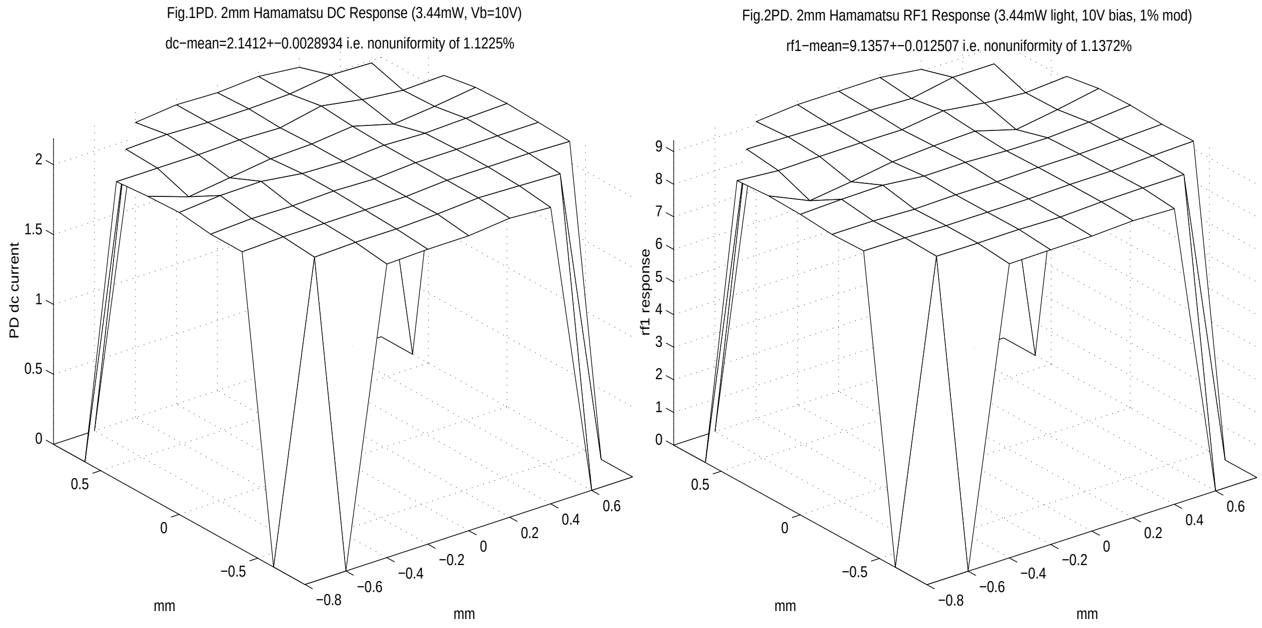


Figure 3: DC(left) and RF(right) spatial uniformity of the G5832-2 PD

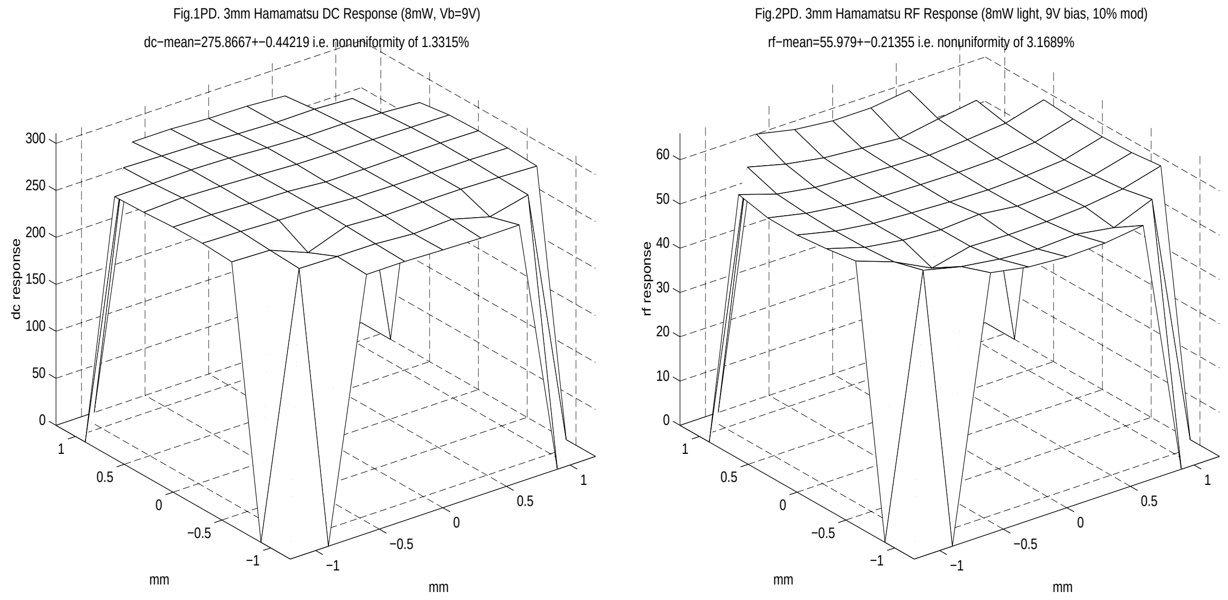


Figure 4: DC(left) and RF(right) spatial uniformity of the G5832-3 PD

PD Opto-Electrical Properties (2)

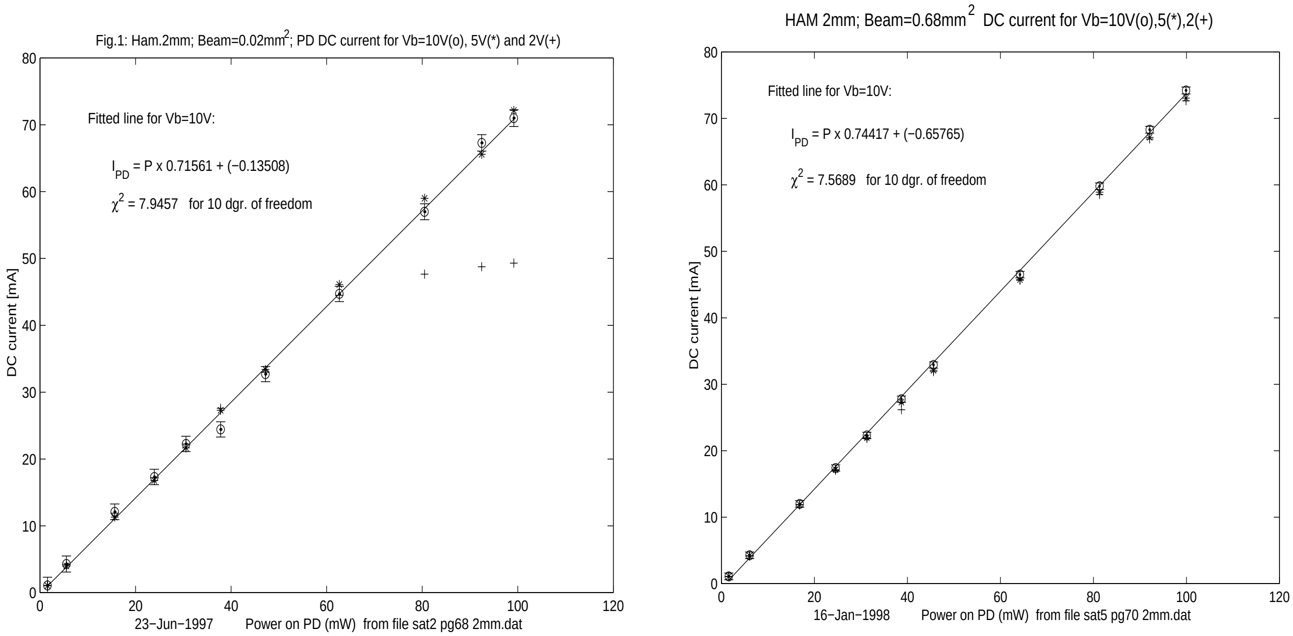


Figure 5: DC response of G5832-2 at various bias Voltages and Beam sizes. Modulation 1%

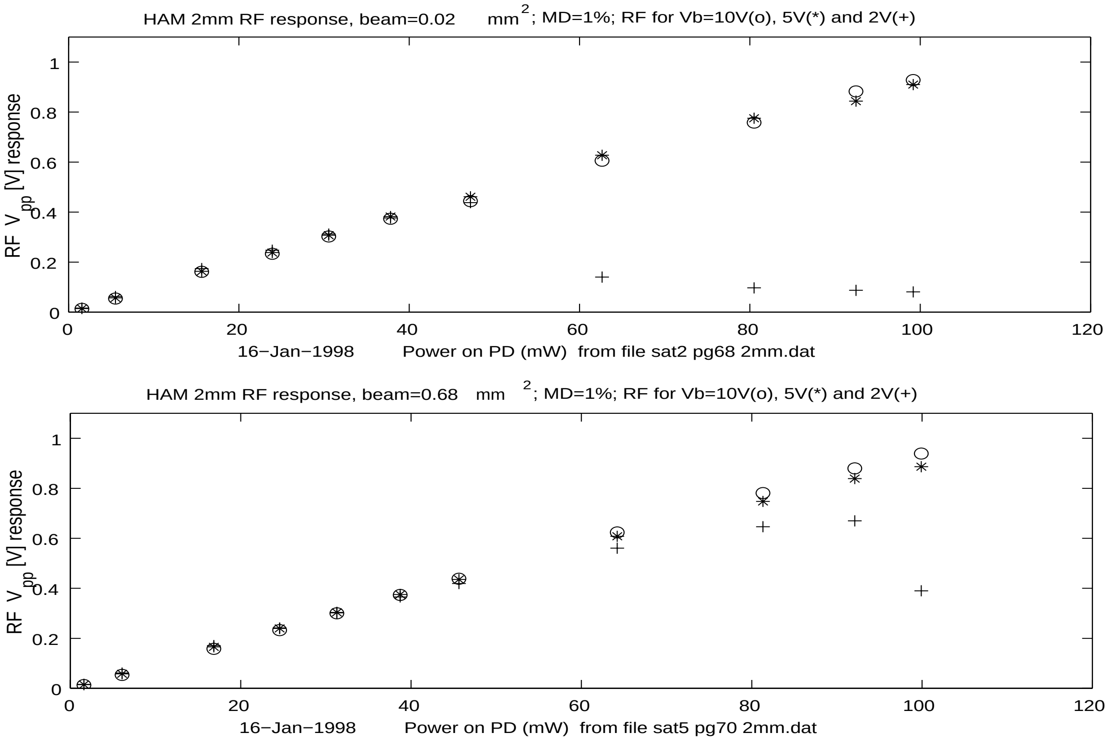


Figure 6: RF response of G5832-2 at various bias Voltages and Beam sizes. Mod 1%

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

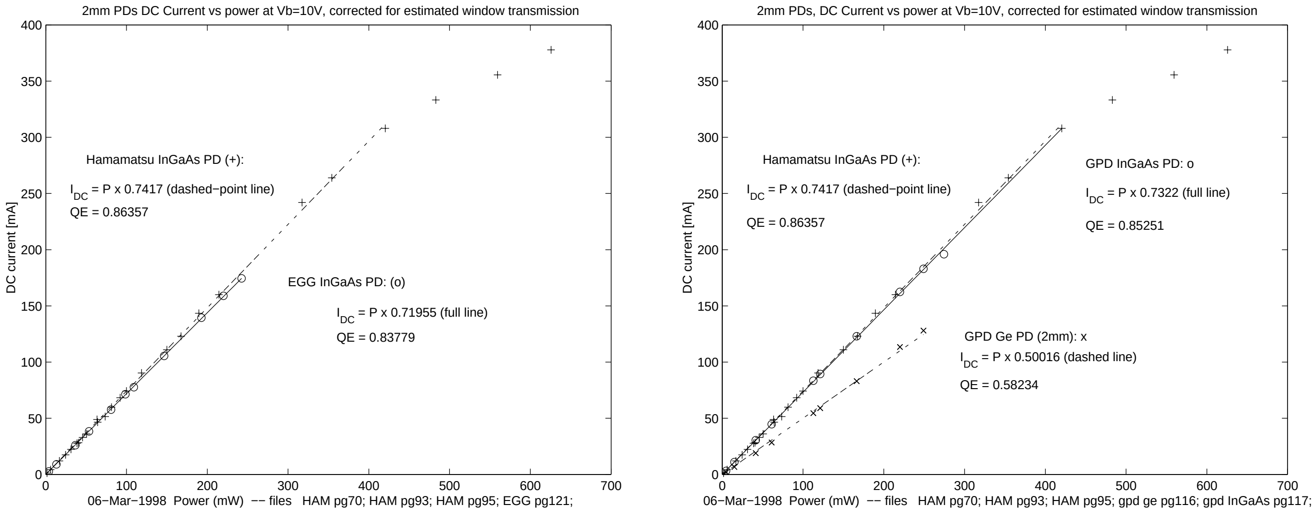


Figure 7: 2mm PDs: DC response of EG&G and HAM (left); GPD and HAM (right)

- *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:

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

PD Opto-Electrical Properties (5)

››RF Response at Various Power Levels

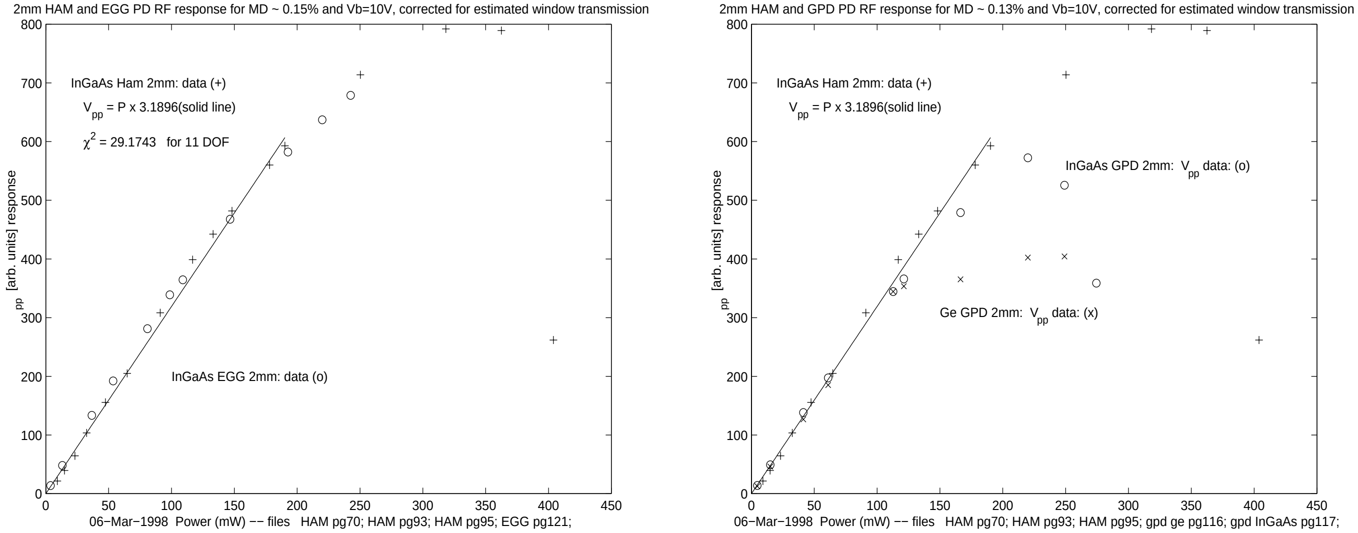


Figure 8: 2mmPD: RF response of EG&G and HAM (left); GPD and HAM (right)

- *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 d**	**# 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)	18	1100	<1[c]	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 10 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).

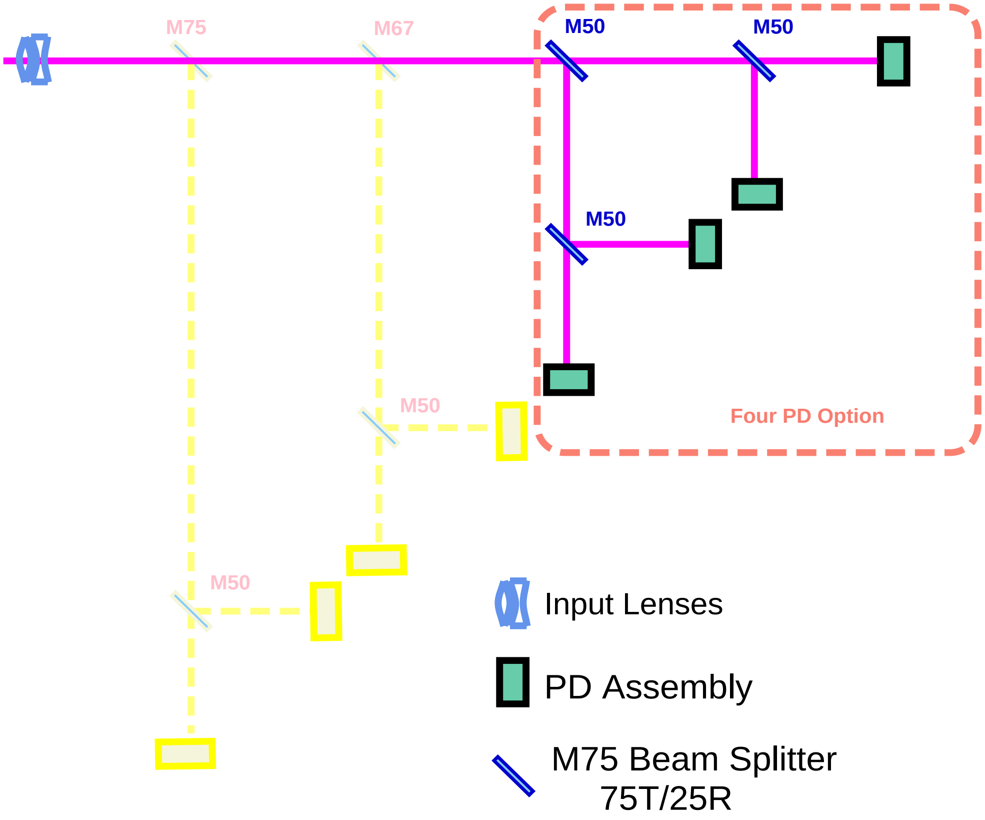
d. VIRGO custom diode (parameters communicated by R. Flaminio).

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.

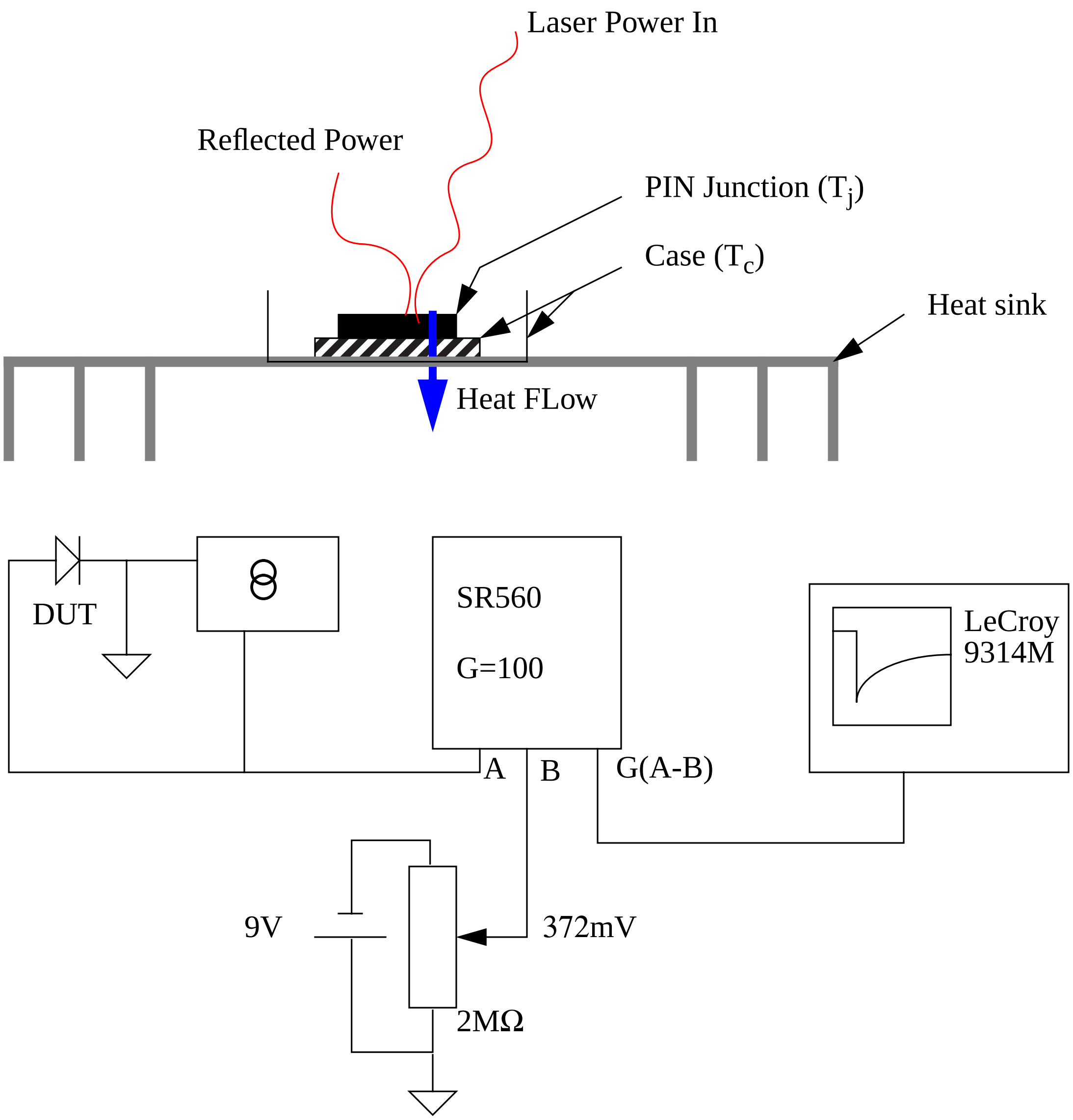


Photodiode Assembly

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

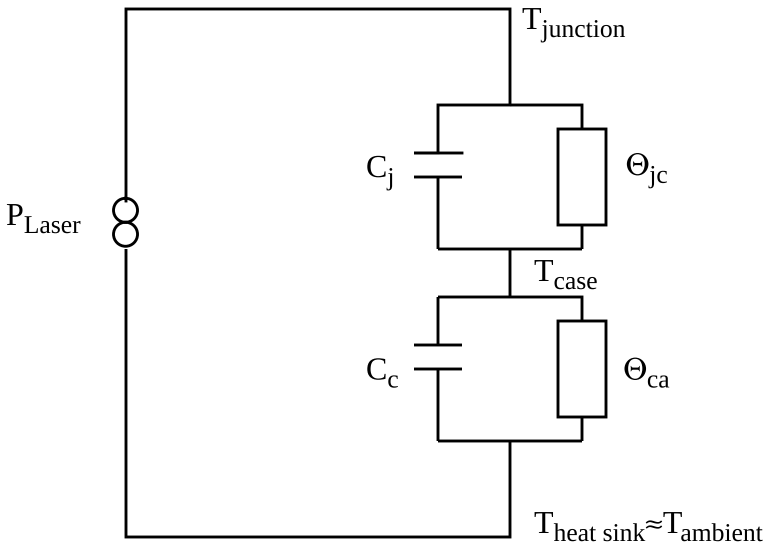
Thermal Impedance

- Measurement setup



Thermal Impedance

- Equivalent Thermal “Circuit” Model



- Solution

$$T_j(t) = P_{Laser}\left[\Theta_{jc} e^{-\frac{t}{\Theta_{jc}C_j}} + \Theta_{ca} e^{-\frac{t}{\Theta_{ca}C_c}}\right]$$

Thermal Impedance

- Results

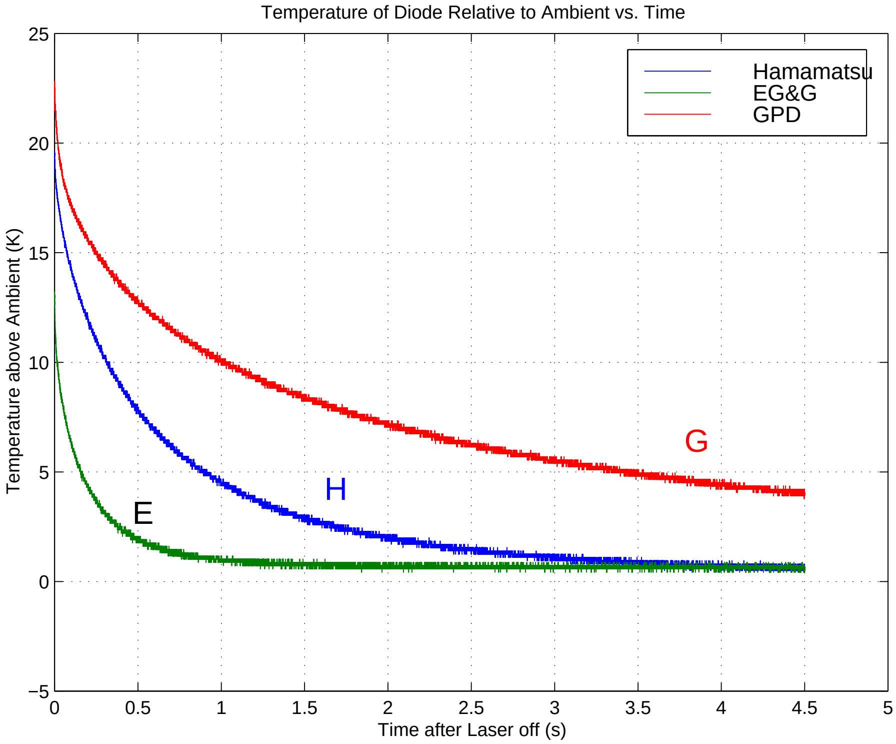


Table 1: 2mm Diode Thermal Impedances

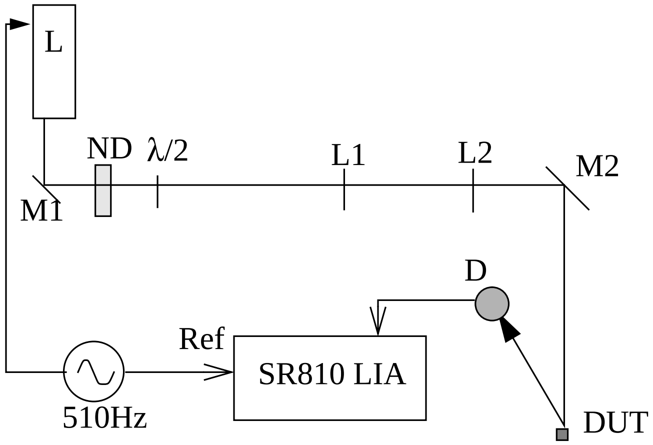
Diode	Thermal Impedance (K/W)	Approx[a]. Time Constant (s)
Hamamatsu (G5832-2)	25	0.57
EG&G (C30642G)	17	0.16
GPD (GAP2000)	28	1.6

[a] This is the time it takes for the traces in the above figure to fall to 1/e of their initial values. It ignores the second time constant predicted by the solution on the pervious page

Diode Reflectivity

GPD

- Setup



L - Laser (1.064µm)

L1, L2 - Lenses

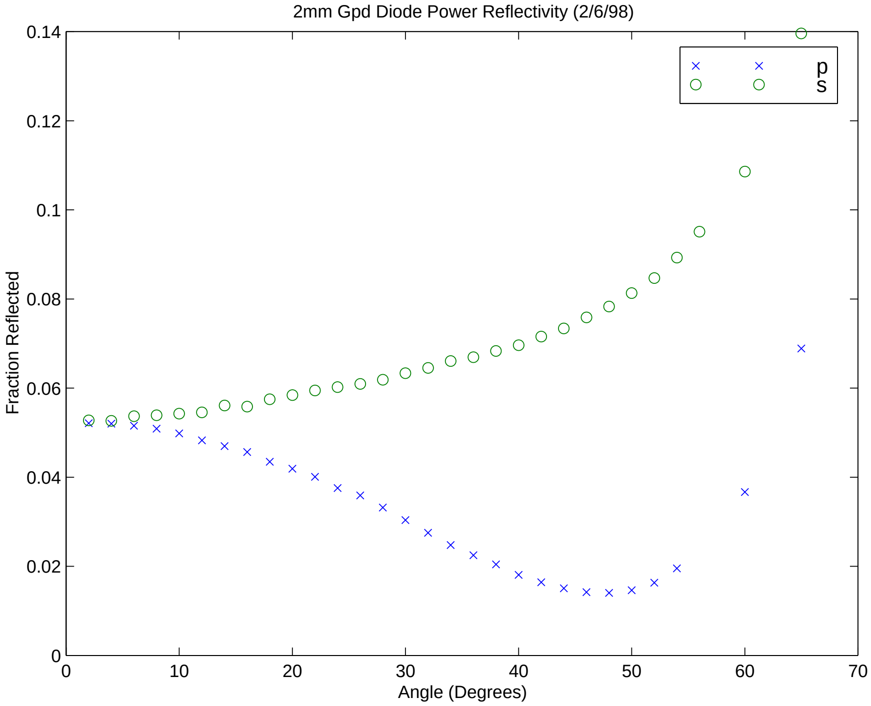
ND - Neutral Density Filter

λ/2 - Halfwave plate

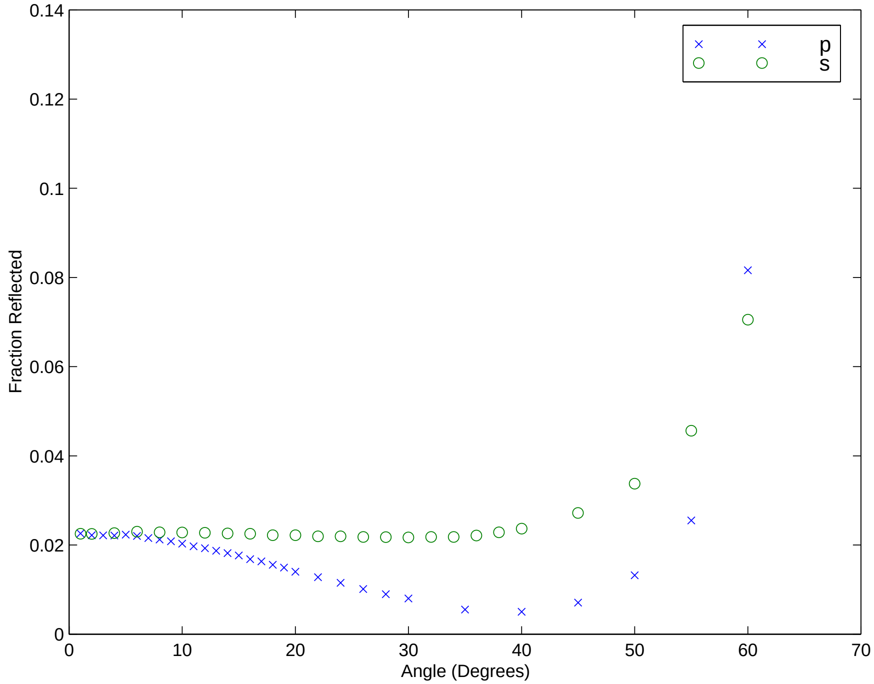
DUT - Diode under test

D - Detector

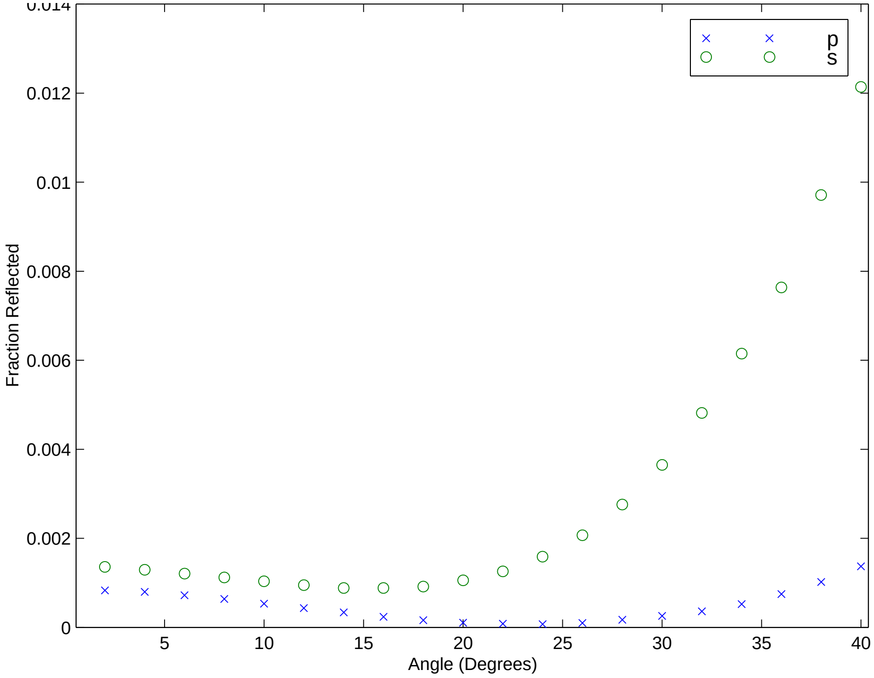
- GPD



Diode Reflectivity EG&G and Hamamatsu



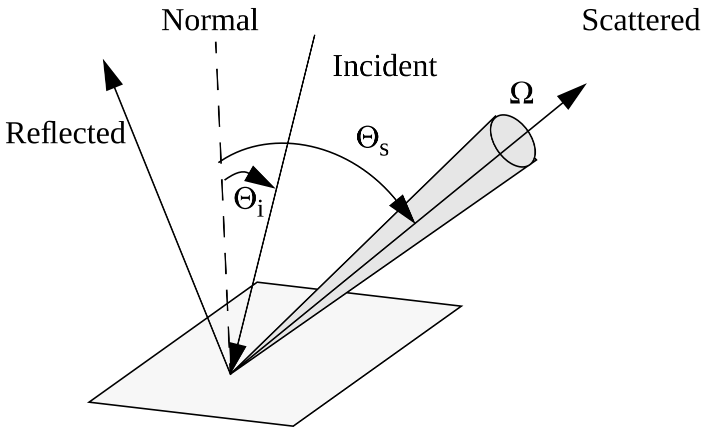
EG&G



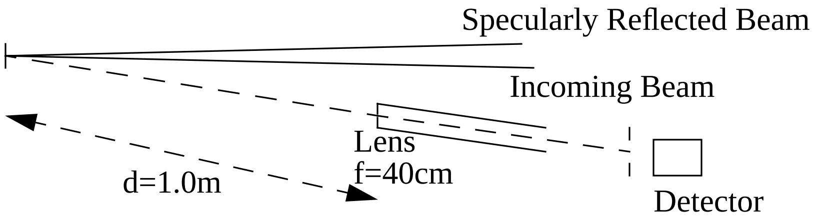
Hamamatsu

Diode BRDF

- Definition



- Setup



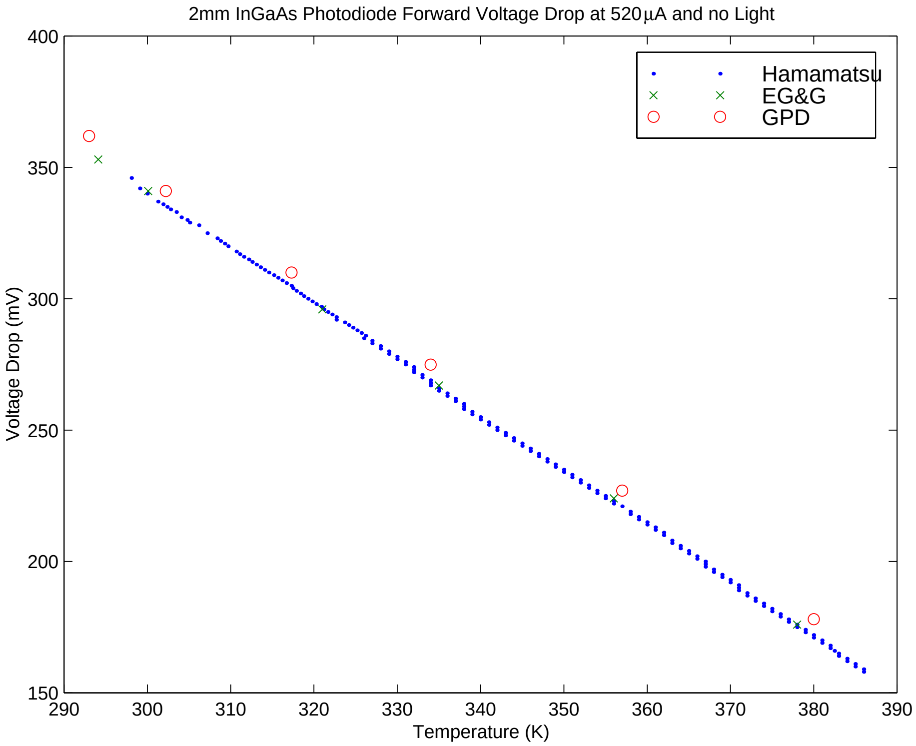
- Results

Table 2: 2mm Diode Backscatter

Diode	BSDF (BRDF) at 6.5° (10^{-4}/ster)
Hamamatsu (G5832-2)	1.1
EG&G (C30642G)	0.37
GPD (GAP2000)	0.11

Forward Voltage Drop

- Calibration Curve
  - ›› Temperature Coefficient: -2.1 mV/K



PD Specs Scaled to LIGO II Power and Sensitivity

Parameter	*LIGO I*	*LIGO II*	*Current design*
Steady-state power	0.6 W	3.0 W[a]	0.75 W
Transient damage	3 J / 10 ms	30 J / 10 ms	3 J / 10 ms
Signal/Noise	1.4×10^{10} Hz$^{1/2}$	3.1×10^{10} Hz$^{1/2}$	1.5×10^{10} Hz$^{1/2}$
Quantum efficiency	80%	90%	83%
Spatial uniformity	1% RMS	0.1% RMS	1% RMS
Surface backscatter	10^{-4} /sr	10^{-5} /sr[b]	$< 10^{-4}$/sr

a. Assuming a factor of two improvement in contrast defect

b. Assuming comparable active detector area.