LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY

LIGO Laboratory / LIGO Scientific Collaboration

LIGO-T1100402-v2 LIGO August 17, 2011

ISC RF Photodetector Design: LSC & WFS

Rich Abbott, Rana Adhikari, Peter Fritschel

Distribution of this document:
LIGO Scientific Collaboration

This is an internal working note
of the LIGO Laboratory.

California Institute of Technology
LIGO Project – MS 18-34
1200 E. California Blvd.
Pasadena, CA 91125
Phone (626) 395-2129
Fax (626) 304-9834
E-mail: info@ligo.caltech.edu

Massachusetts Institute of Technology
LIGO Project – NW22-295
185 Albany St
Cambridge, MA 02139
Phone (617) 253-4824
Fax (617) 253-7014
E-mail: info@ligo.mit.edu

LIGO Hanford Observatory
P.O. Box 159
Richland WA 99352
Phone 509-372-8106
Fax 509-372-8137

LIGO Livingston Observatory
P.O. Box 940
Livingston, LA 70754
Phone 225-686-3100
Fax 225-686-7189

http://www.ligo.caltech.edu/

1 Introduction

This document describes the design of the RF (radio-frequency) photodetectors used in the Advanced LIGO ISC subsystem for sensing the length and alignment degrees-of-freedom of the interferometer. These include what is traditionally called a 'LSC RF PD'—for length sensing – and the wavefront sensor (WFS), for alignment sensing. The list of ISC detectors (RF & DC) can be found in T1000264.

2 Design requirements

The qualitative design requirements that apply to both the LSC and WFS RF detectors are:

- Capability of simultaneous readout at two RF frequencies
- Capable of operation at 50-100 ma of average photocurrent
- Photodetector noise equivalent to shot noise of several milliamps or less photocurrent
- Readout of DC photocurrent (DC—10+ kHz) with reasonable SNR
- Signal injection input for amplifier testing, and possible correction input (e.g., AS_I correction)
- Rejection of RF harmonic/intermodulation frequencies to avoid amplifier non-linearity
- Packaging styles for in-air and in-vacuum use, where the design concept for the vacuum version is: amplifier is mounted in a vacuum-sealed metal box, with hermetic, vacuum-compatible feedthrus for electrical connections and the photodiode (i.e., the photodiodes are outside the box, in the vacuum environment)

2.1 Specific requirements for LSC detectors

Requirements for the LSC RF detectors at the REFL (PRM reflection) and POP (PRC pick-off) ports:

RF detection frequency, f1	9 MHz
RF detection frequency, f2	45 MHz
Bandwidth at each RF frequency	>= 100 kHz
Noise at f1, shot-noise equivalent	< 3 ma
Noise at f2, shot-noise equivalent	< 3 ma
RF frequencies to reject	18, 36, 54, 90 MHz
DC readout sensitivity, shot-noise equivalent	< 5 ma
Maximum average photocurrent	80 ma

Requirements for the LSC RF detector at the AS (anti-symmetric) port, where only a single RF frequency readout is required:

RF detection frequency, f1	NA
RF detection frequency, f2	45 MHz
Bandwidth at each RF frequency	>= 100 kHz
Noise at f1, shot-noise equivalent	NA
Noise at f2, shot-noise equivalent	< 3 ma
RF frequencies to reject	90 MHz
DC readout sensitivity, shot-noise equivalent	< 5 ma
Maximum average photocurrent	5 ma

2.2 Specific requirements for WFS

Requirements for the WFS detectors at the REFL (PRM reflection) port, for each quadrant channel:

RF detection frequency, f1	9 MHz
RF detection frequency, f2	45 MHz
Bandwidth at each RF frequency	>= 1 kHz
Noise at f1, shot-noise equivalent	< 3 ma
Noise at f2, shot-noise equivalent	< 3 ma
RF frequencies to reject	18, 36, 54, 90 MHz
DC readout sensitivity, shot-noise equivalent	< 5 ma
Maximum average photocurrent, per segment	10 ma

Requirements for the WFS detectors at the AS port, for each quadrant channel:

RF detection frequency, fm	36 MHz
RF detection frequency, f2	45 MHz
Bandwidth at each RF frequency	>= 1 kHz
Noise at fm, shot-noise equivalent	< 1 ma
Noise at f2, shot-noise equivalent	< 1 ma
RF frequencies to reject	90 MHz
DC readout sensitivity, shot-noise equivalent	< 5 ma
Maximum average photocurrent, per segment	3 ma

3 Photodiodes

For the LSC detectors the photodiode is the same as we have been using in the iLIGO/eLIGO RF PDs: Perkin Elmer C30642G, 2 mm diameter InGaAs PIN photodiodes. The datasheet for this diode is in the DCC: C30642G datasheet. At the operating reverse bias (7 V), the nominal circuit parameters of the diode are: series resistance = 6.7 ohms; capacitance = 102 pF.

For the WFS detectors, we use a InGaAs quadrant photodiode from OSI Optoelectronics, model FCI-InGaAs-Q3000. This diode is 3 mm in diameter. The electrical parameter characterization of the Q3000 is described in T1100029. The measured parameters are (@ 5 V reverse bias, and 45 MHz): series resistance = 23 ohms; capacitance = 110 pF.

4 Amplifier design

The amplifier for both the LSC and WFS detectors uses the series resonant design concept described by H. Grote[1]. Compared to the parallel resonant circuit readout used in initial LIGO, this design easily accommodates multi-frequency readout; it also presents a lower impedance to the photodiode at the readout frequency, which in principle should reduce non-linear effects in the diode. Another advantage is that the resonant tuning is not so dependent on the photodiode parameters, so that a photodiode can be replaced without retuning the circuit – a particular advantage for the in-vacuum detectors.

[1] *High power, low-noise, and multiply resonant photodetector for interferometric gravitational wave detectors,* H. Grote, Rev. Sci. Inst., **78**, 054704 (2007).

4.1 Generic circuit model & optimization

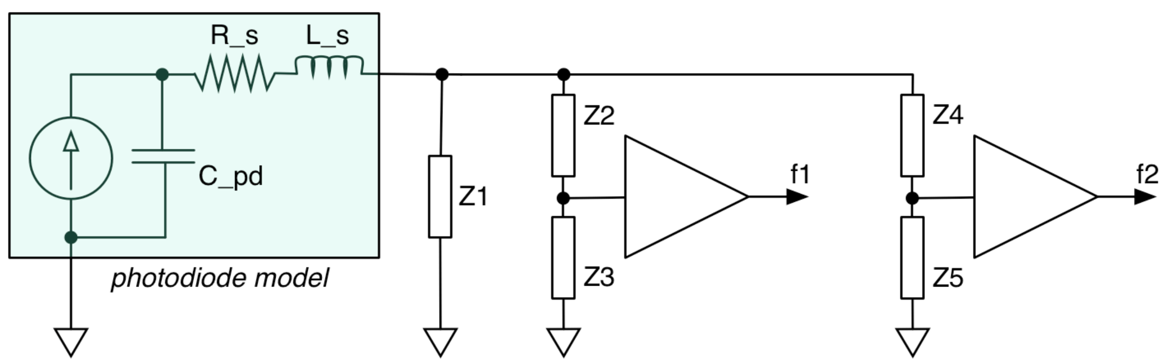


Figure 1. Generic circuit model of a two-frequency detector.

The generic circuit model of a two-frequency, series resonant readout detector is shown in Figure 1. This model is used for circuit optimization, where a cost function is defined and minimized by searching over values of the impedances (Z1, … Z5). The type of cost function used so far looks like:

$$\frac{a_1}{SNR_1} + \frac{a_2}{SNR_2} + a_3\left(\frac{P_{\text{un-freqs}}}{P_{\text{sig-freq}}}\right),$$

where SNR_i is the signal-to-noise ratio for shot-noise at output I, $P_{\text{un-freqs}}$ is the output power at unwanted frequencies (at $2*f_1$, e.g.), $P_{\text{sig-freq}}$ is the output power at the signal frequency, and a_i are weighting factors.

4.2 Op-amp

Traditionally the LIGO RF detectors have used the MAXIM 4107 high-speed, ultra-low noise op-amps. These parts are now obsolete; the MAXIM replacements for the 4106/4107 all have much higher input voltage noise – too high for our use. Fortunately, the National LMH6624 looks like a nice replacement. Here is a comparison of their key performance parameters:

Parameter	LMH6624	MAX4107
Input voltage noise	0.92 nV/√Hz	0.75 nV/√Hz
Input current noise	2.3 pA/√Hz	2.5 pA/√Hz
-3 dB bandwidth, $A_v = +10$	200 MHz	300 MHz
Slew rate, $A_v = +10$	400 V/µs	500 V/µs
2^{nd} harmonic distortion, $A_v = +10$, V_o=2 Vpp, 10 MHz, R_L=100ohm	-68 dB	-53 dB

4.3 DC photocurrent readout

For the LSC detectors, the DC readout may be used for noise investigations, and so it should be capable of shot-noise limited performance at the nominal operating level. For the WFS, the DC signals on the diode segments are used for beam centering on the quadrant diodes. The DC photocurrent is pulled out through a transimpedance amplifier stage, with a nominal transimpedance of 100 ohms (kept relatively low in order to handle up to 100 ma of photocurrent; this could be increased for the WFS). To be able to source the photocurrent, this stage is a combination of a low-noise input opamp (AD8597) followed by a high-current buffer (HA5002).

For the LSC detectors, the transimpedance stage is followed by a whitening (high-frequency boost) stage. This consists of a unity gain DC path, in parallel and summed with an AC-coupled, high gain path. The resulting transfer function has unity gain at DC, 21 dB gain above 5 Hz, with a zero at 0.24 Hz and pole at 2.4 Hz. Following the whitening stage is a differential output stage. The 3 dB bandwidth of the DC path is about 200 kHz.

4.4 RF Test Input

As shown in Figure 2, the RF Test Input is implemented by a common base transistor, Q2, which forms a voltage to current transconductance amplifier. The input impedance of the circuit is set by R2 in conjunction with the dynamic emitter resistance of Q1 (~3Ω). The key specifications of this transistor circuit are shown in Table 1.

Figure 2, RF Test Input Schematic

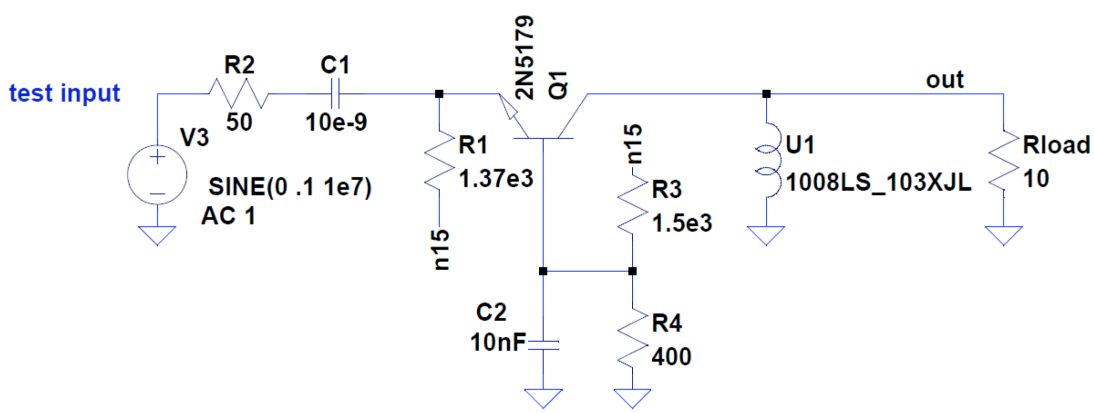


Table 1. RF Test Input Specifications

Parameter	Value
Transconductance (10MHz to 100MHz)	18mS, +/- 0.1mS
Low Frequency -3dB point	400 kHz
High Frequency -3dB point	800 MHz
Input Referred Noise (10 MHz to 100 MHz)	2.5nV rms /√Hz
Max Input Drive for ≤ 1% Amplitude Distortion	-4dBm @ 10 MHz
Quiescent DC Emitter Current	8mA

An RF current source was chosen for the test input to ensure negligible loading of the complex RF circuitry and predictable gain. An RF relay (see U10 in Figure 3) is used to disconnect the current source from the rest of the circuitry during normal operation of the detector. A resistive test output path formed by R15 and C8 in Figure 3 is included in the design. R16 is only present in the spice model, and represents the input impedance of some piece of RF test equipment.

4.5 Specific designs

Schematics for the LSC and WFS detectors can be found in:

LSC RF PD Schematic	D1101124
WFS Schematic	D1101614

4.5.1 9 & 45 MHz LSC detector

The design for the LSC 9 & 45 MHz detector is shown in Figure 3. The REFL port contains significant signal at several of the RF harmonics, which forces the use of multiple LC notch filters in the design.

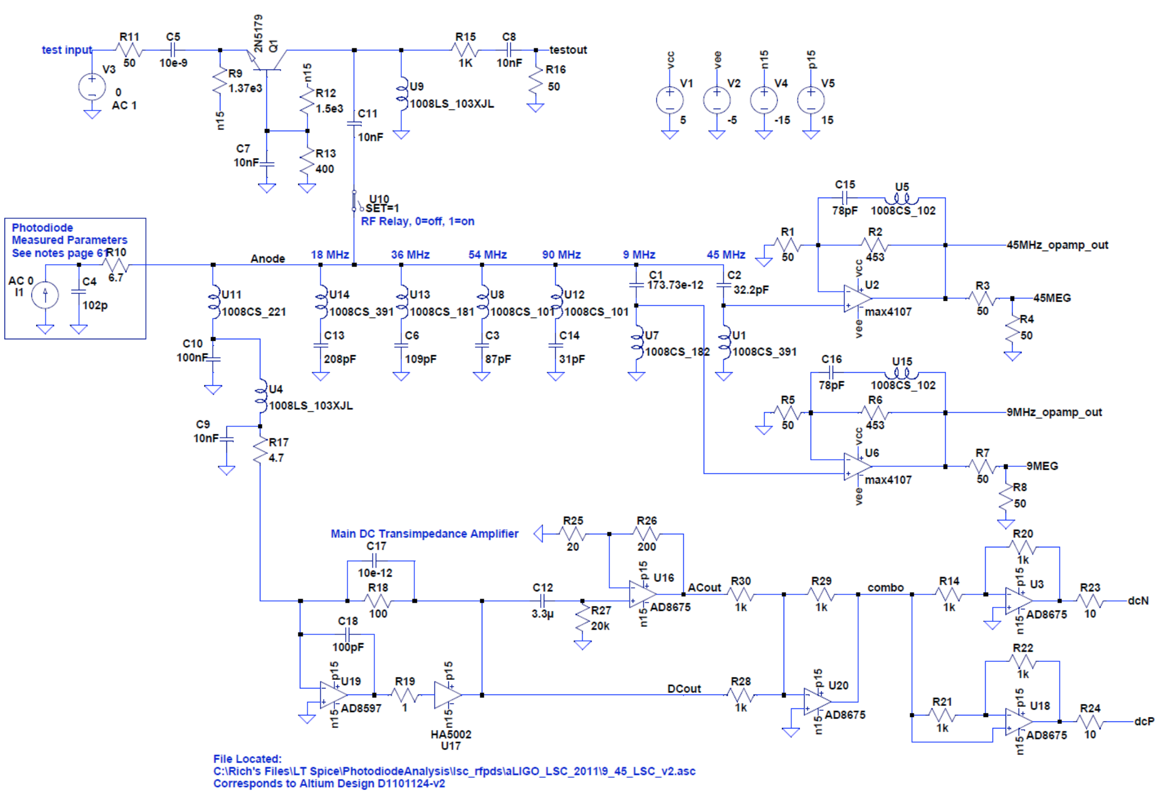


Figure 3. Spice model for the LSC 9 & 45 MHz detector. (The MAX4107 is used because the LMH6624 is not in the spice library.)

Parameter	Spice value
Transimpedance: 9 MHz op-amp output	311 ohms
Transimpedance: 45 MHz op-amp output	490 ohms
Shot noise limit: 9 MHz output	1.3 ma
Shot noise limit: 45 MHz output	2.0 ma
Shot noise limit: DC output	3.5 ma (4 ma @50 Hz)

Table 2. Gain and noise performance for the 9 & 45 MHz LSC detector, as calculated by the above Spice model

Freq. component	Output	Gain	Photocurrent	V op-amp
18 MHz	9 MHz	4.0 ohm	16 ma	64 mV pk
	45 MHz	0.6 ohm		10 mV pk
36 MHz	9 MHz	7.0 ohm	9 ma	63 mV pk
	45 MHz	11.0 ohm		100 mV pk
54 MHz	9 MHz	9.0 ohm	3.4 ma	31 mV pk
	45 MHz	31.0 ohm		105 mV pk
90 MHz	9 MHz	17.0 ohm	4.6 ma	78 mV pk
	45 MHz	22.0 ohm		101 mV pk

Table 3. Frequency rejection for the 9 & 45 MHz LSC detector. Spice model includes 18 MHz notches in the feedback of each op-amp. The photocurrents at the various frequencies come from T0900511-v4 (table A.3), and are scaled to a total DC photocurrent of 80 ma. The notches at these frequencies are required to keep the signal level at the op-amp output well below 1 V pk ('V op-amp' is the voltage at the output pin of the op-amp).

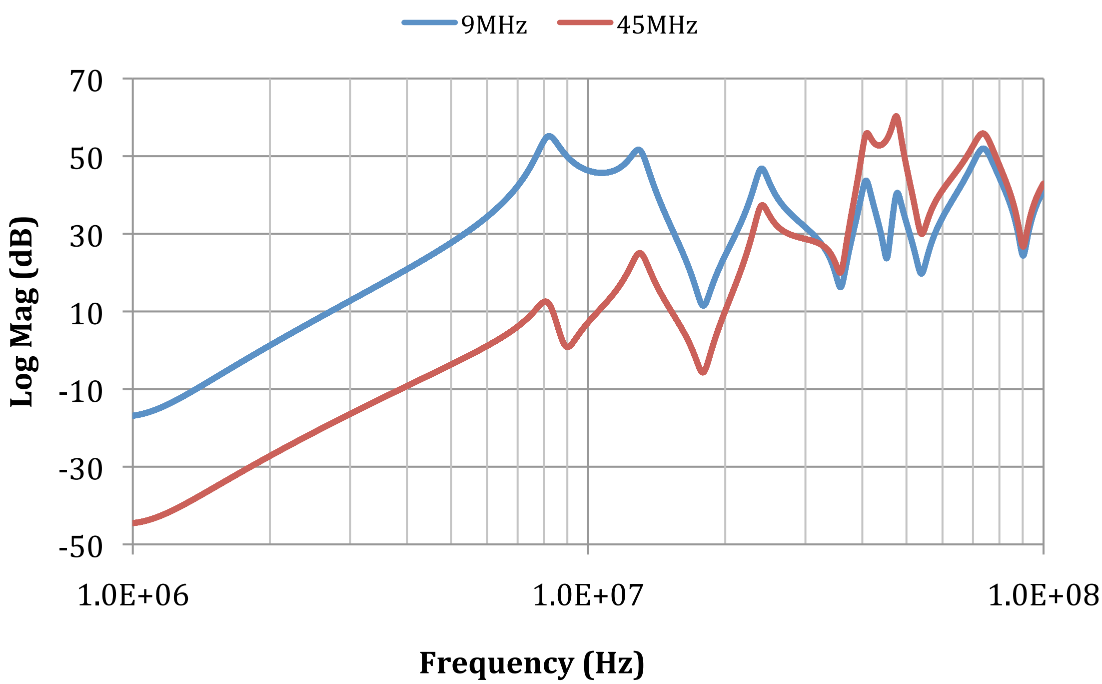


Figure 4. Transfer functions for the 9 & 45 MHz LSC detector (volts/amp). Input for the transfer functions is photocurrent, output is at the corresponding op-amp output pin.

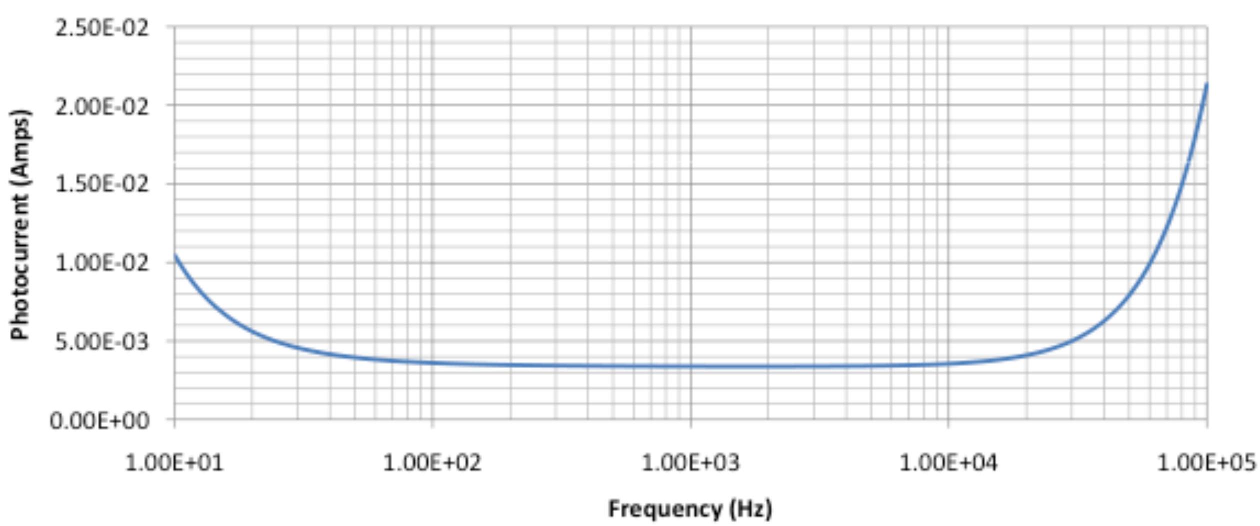


Figure 5. Sensitivity of the DC readout of the 9/45 MHz LSC photodetector. Plotted is the DC photocurrent for which the shot noise is equal to the electronics noise at the DC output.

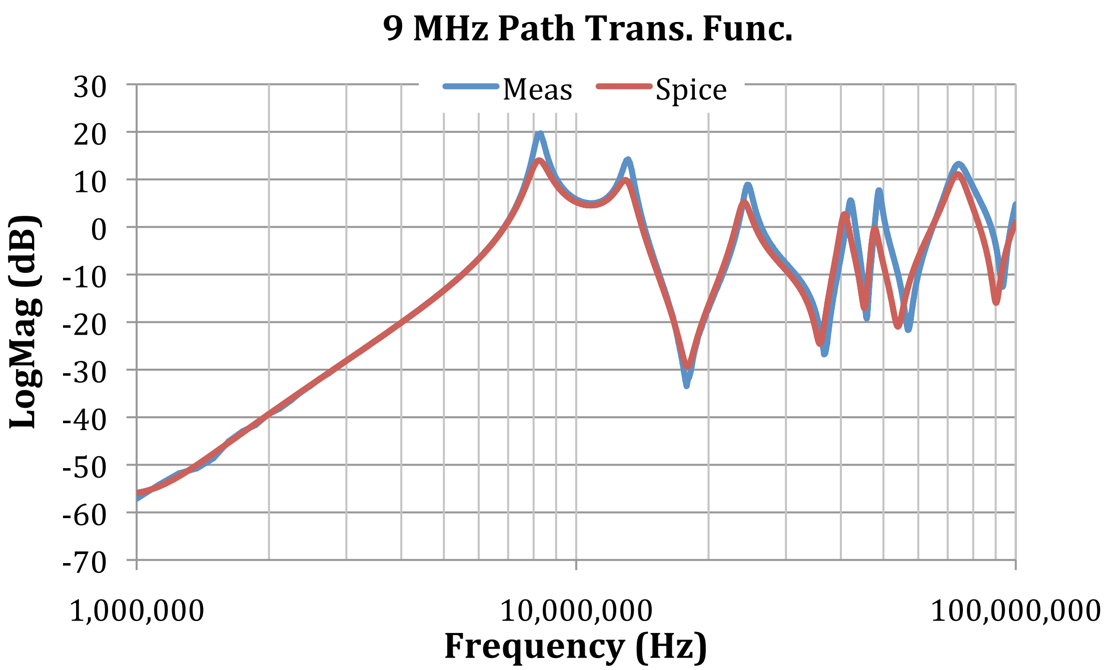


Figure 6. Overlay of measured vs. SPICE transfer function from the Test Input to the 9 MHz RF output connector.

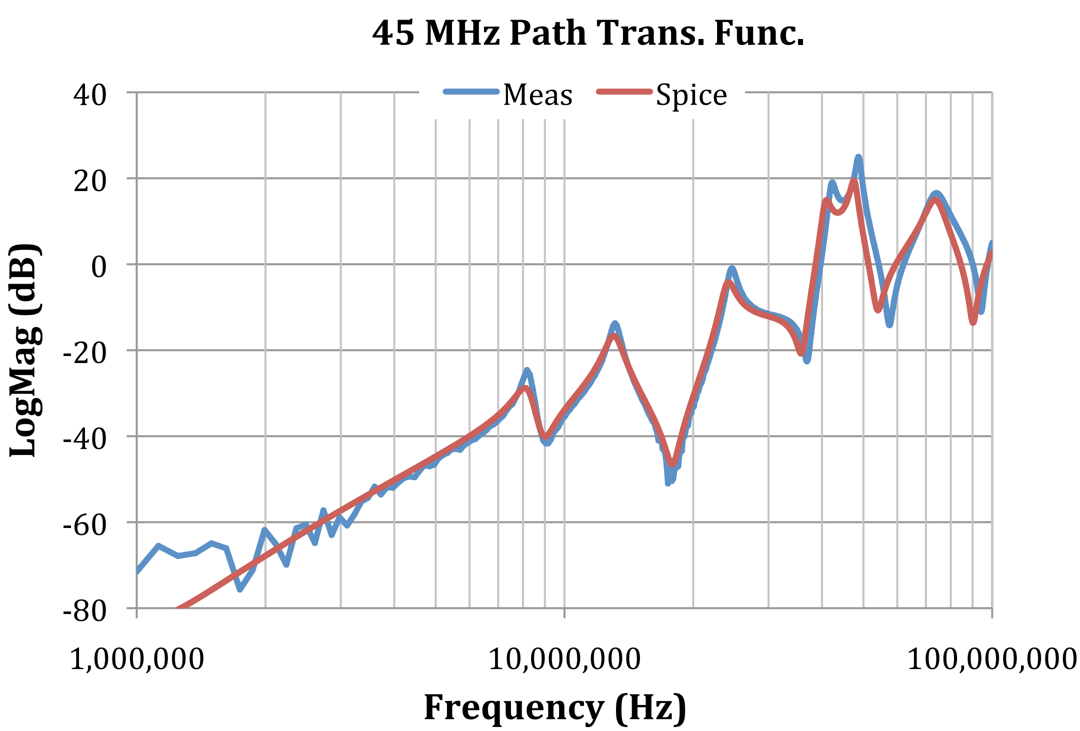


Figure 7. Overlay of measured vs. SPICE transfer function from the Test Input to 45 MHz RF output conector.

4.5.2 45 MHz LSC detector

The 45 MHz LSC detector (for the AS port) can either be the same as a 9/45 MHz LSC detector, or a simplified version of that where only the 45 MHz readout is implemented.

4.5.3 9 & 45 MHz WFS

The requirements for this WFS are very similar to the 9/45 MHz LSC detector, except that each channel does not need to handle as much photocurrent. The design is thus very similar to the LSC detector.

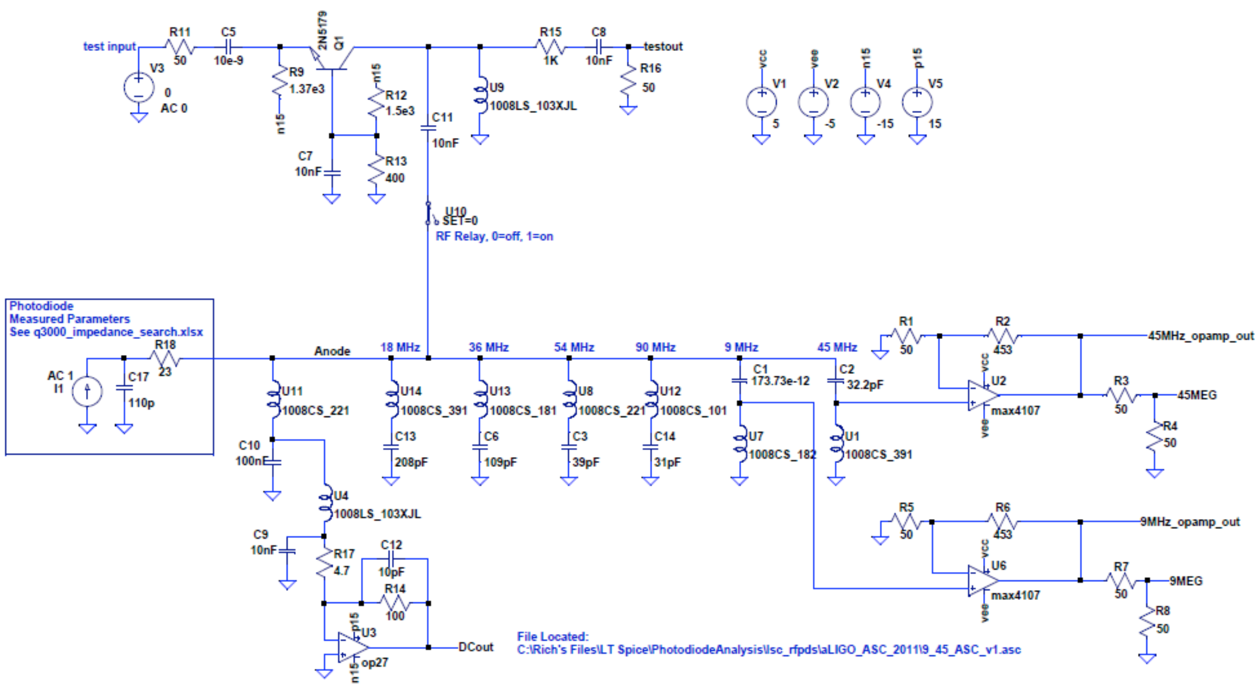


Figure 8. Spice model for the 9/45 MHz WFS.

Parameter	Spice value
Transimpedance: 9 MHz op-amp output	838 ohms
Transimpedance: 45 MHz op-amp output	813 ohms
Shot noise limit: 9 MHz output	1.4 ma
Shot noise limit: 45 MHz output	2.4 ma
Shot noise limit: DC output	3 ma (3.4 ma @10 Hz)

Table 4. Gain and noise performance for the 9 & 45 MHz WFS detector, as calculated by the above Spice model.

Freq. component	Output	Gain	Photocurrent	V op-amp
18 MHz	9 MHz	33 ohm	2.0 ma	66 mV pk
	45 MHz	5.0 ohm		10 mV pk
36 MHz	9 MHz	15 ohm	1.1 ma	18 mV pk
	45 MHz	25 ohm		28 mV pk
54 MHz	9 MHz	17 ohm	0.4 ma	7 mV pk
	45 MHz	53 ohm		21 mV pk
90 MHz	9 MHz	10 ohm	0.6 ma	6 mV pk
	45 MHz	13 ohm		8 mV pk

Table 5. Frequency rejection for the 9 & 45 MHz WFS detector. The photocurrents at the various frequencies come from T0900511-v4 (table A.3), and are scaled to a total DC photocurrent of 10 ma. The notches at these frequencies are required to keep the signal level at the op-amp output well below 1 V pk ('V op-amp' is the voltage at the output pin of the op-amp).

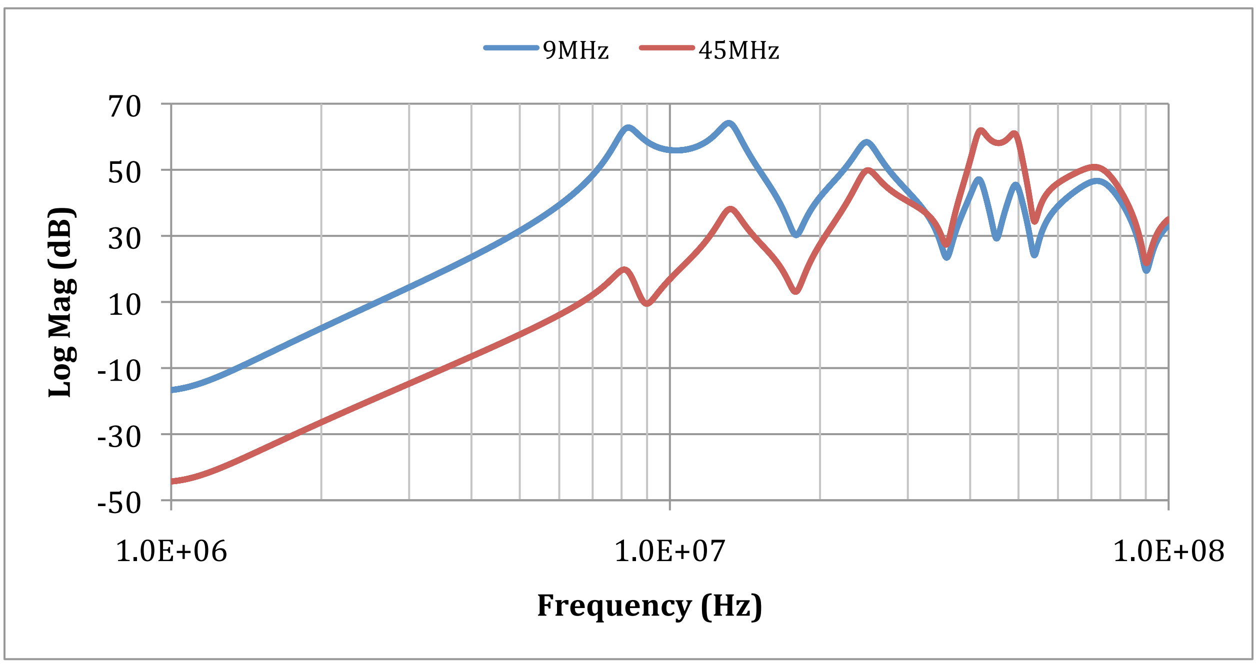


Figure 9. Transfer functions for the 9 & 45 MHz WFS detector (volts/amp). Input for the transfer functions is photocurrent, output is at the corresponding op-amp output pin.

4.5.4 36 & 45 MHz WFS

This case presents the most challenging design in terms of signal-to-noise ratio, since we need to limit the power to a small fraction of the AS port power. We typically assume 1% of the total AS port power for the WFS, and at full power operation this translates to 5-6 mW, or 2.5-3 mW on each of the two AS port WFS. The other constraint is that with the differential arm cavity offset required for DC readout, there is a constant 45 MHz signal in each WFS channel. The WFS transimpedance gain at 45 MHz thus must not be too high, to keep the op-amp operating within its linear region.

5 Packaging

5.1 In-vacuum packaging

The basic packaging design for the in-vacuum detectors is to mount the circuit board in a vacuum-sealed aluminum box, with hermetic feedthrus for the electrical connectors and the photodiode. Thus the photodiode resides in the vacuum environment (and must be vacuum qualified), and simply plugs into a socket on the detector box.

Laser welding is used to mount the feedthrus on the boxes, and to seal the boxes once the circuit boards are installed inside. The feedthrus, boxes, and laser welding are all provided by SRI Hermetics, Inc. SRI also leak tests each unit. Figure 10 shows the feedthru prototypes that have been produced by SRI. The boxes for the in-vacuum detectors have not yet been designed.

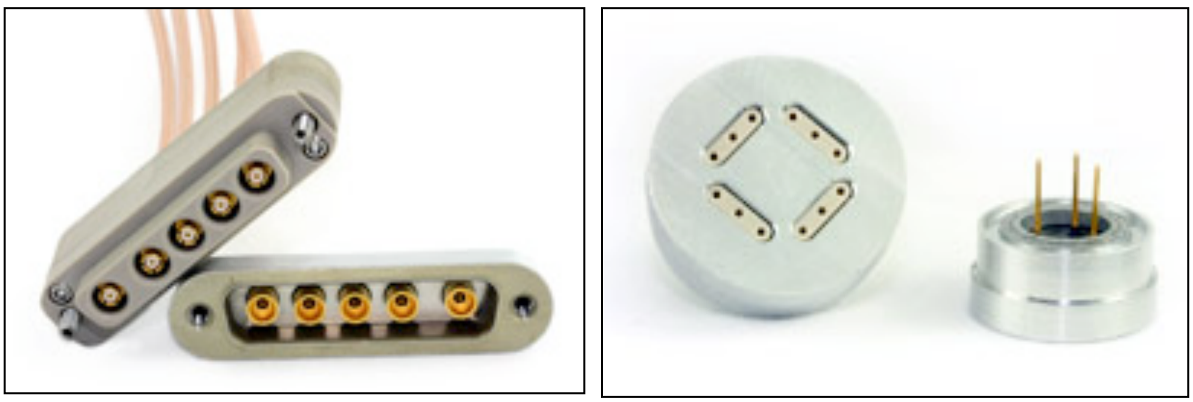
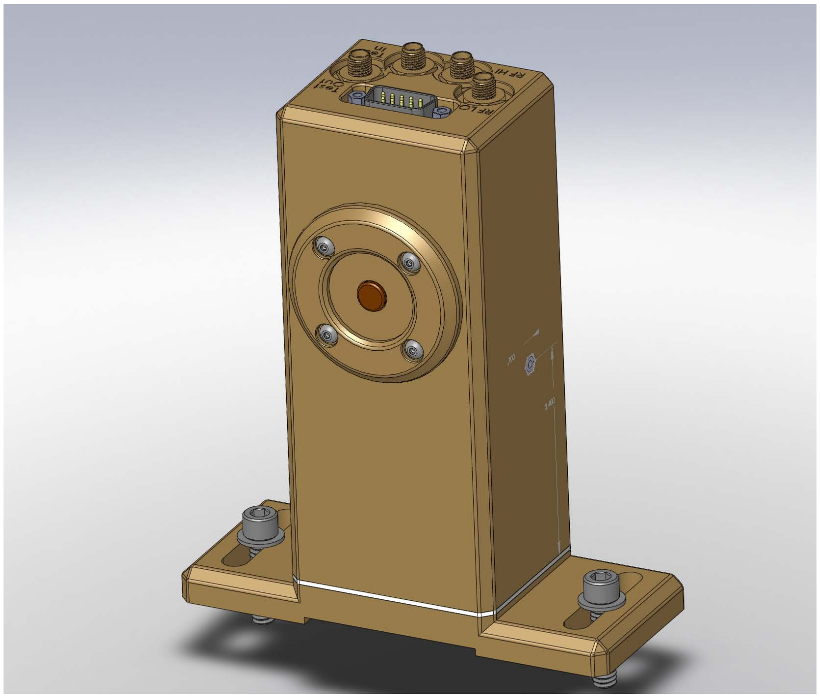


Figure 10. Photodiode feedthrus for the in-vacuum RF detectors. Left: quad photodiode feedthru; photo shows the side the diode plugs into. Right: single element feedthru; photo shows the side that mates to the circuit board. The aluminum holders are laser-welded into an aluminum box that contains the circuit board.

5.2 In-air detector packaging

The designs for the in-air photodetectors are found in:

LSC RF PD Assembly Drawing	D1101174
WFS Assembly Drawing	D1101200



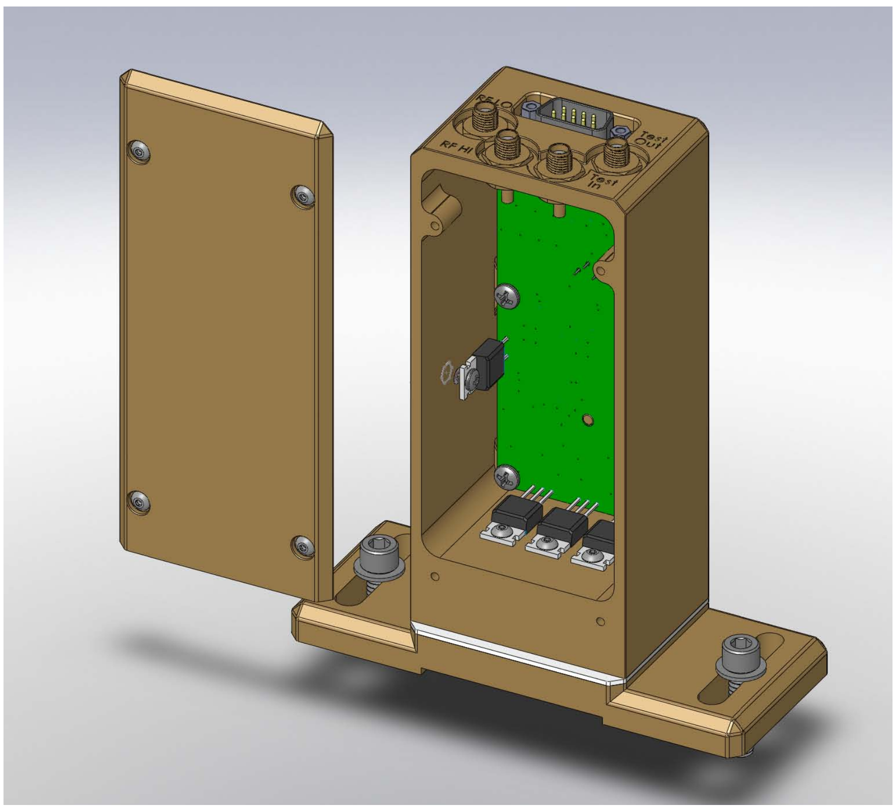


Figure 11. Packaging of the in-air LSC RF PD. Top: front view, showing photodiode. Bottom: rear view, showing circuit board. All electrical connections are at the top of the box. This includes 4 SMA connectors: two for the RF outputs, one test input and one test output. Power, control lines and the DC output are on the 15-pin Dsub connector. The box is approximately 6″ high, 2-3/8″ wide, and 2″ deep (not including protrusions).

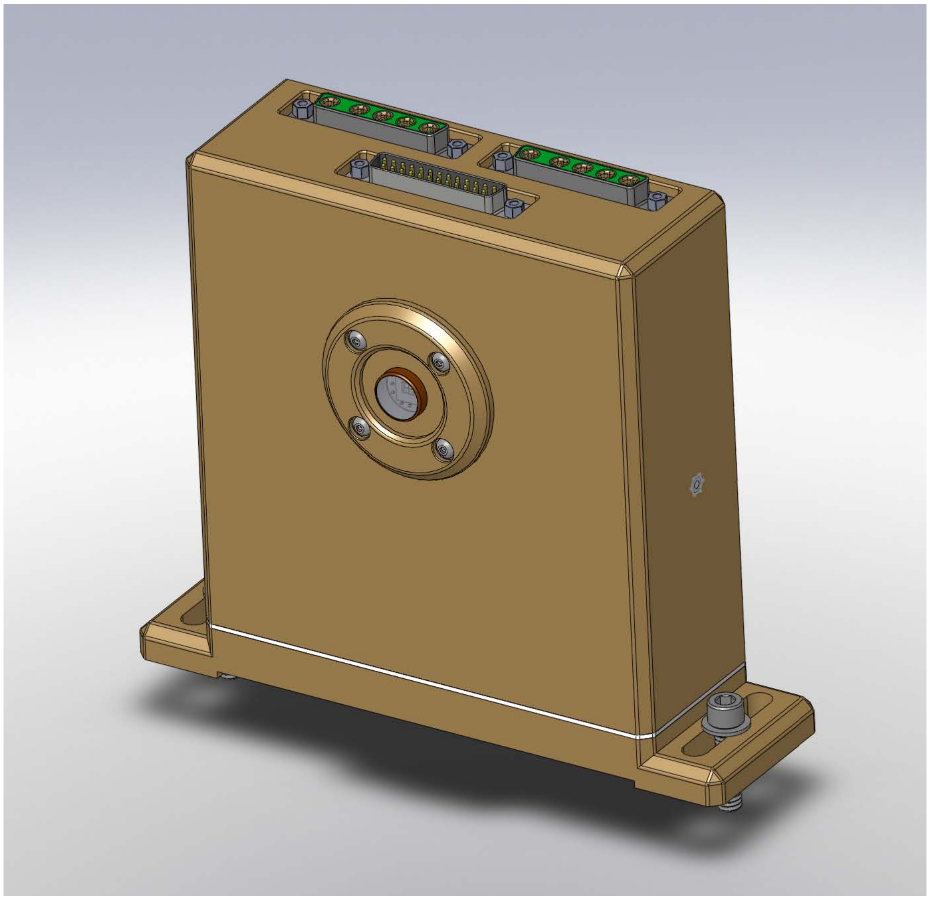


Figure 12. In-air package for the WFS. Photodiode center is at 4 inch height from mounting surface. There are two D-sub, 5-way coax connectors, one for each detection frequency. Each such connector contains the RF outputs for each of the quad segments. One of the D-subs also contains the test input (the remaining coax contact is not used). The box is approximately 6″ high, 5-3/8″ wide, and 2″ deep (not including protrusions).