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ISC Quadrant Photodetector Design

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1 Overview

ISC employs in-vacuum quadrant photo-diodes (QPD) in several places:

- ETM Transmission Monitors: TRX/Y_A&B (arm cavity alignment); ALS_QPDX/Y_A&B (ALS beam alignment)
- HAM6: OMC reflected beam (for OMC alignment); ASC-AS_C (sample of AS port beam, for interferometer alignment)
- HAM3: ASC-POP_A&B (interferometer alignment); MC2 Transmission (IMC alignment)
- HAM2: SM2 Transmission (IO alignment)

This document describes the design of the QPDs and their associated amplifiers for all of these applications. Early versions of this note covered only the Transmission Monitor QPDs, but since then the same design has been adopted for all in-vacuum QPDs, so the document has become more universal.

2 Transmission Monitor QPDs

The alignment control system for aLIGO uses the beams transmitted by the End Test Masses (ETMs) for sensing fluctuations of the arm cavity mode position, as described in T0900511, *Modeling of Alignment Sensing and Control for Advanced LIGO*. For each ETM transmitted beam, there will be two quadrant detectors, to sense both near-field and far-field motions and these detectors will be located within the ETM BSC vacuum chamber on the suspended Transmission Monitor platform (these will be called the TransMon Quads). In addition, two more quadrant detectors will be mounted on this platform to sense the position of the Arm Length Stabilization beam, which is a 532 nm beam injected into the arm from each end station (these will be called the ALS Quads). The two types of quad detectors will use similar mounting and electronics, though the actual photodiodes are different.

For both types of detectors, only the quad diode element will be mounted in the vacuum chamber on the TransMon platform. The amplifier trans-impedance circuitry and associated whitening filters will be located outside the vacuum envelope. A sense-wire type noise cancellation scheme will be employed in a manner identical to the successful ELIGO OMC QPD (see Appendix A). This document contains the design of the trans-impedance amplifiers and whitening filters, details of the photodiodes and diode mounts, and results from prototype electronics. Note with v4 and later versions: this design applies to all in-vacuum ISC quad photodetectors.

3 Photodiodes

For the 1064 nm beam detection, we need to detect up to 50 mW of light at full power operation of the interferometer. We use an InGaAs quad-diode, specifically the OSI Q3000; this is the same diode that will be used in the wavefront sensors (WFSs) and that has been used in eLIGO for invacuum detection of the AS port beam. The diode is in a TO-5 package; the window will be removed (by us), and the resulting package is exposed to the vacuum, so vacuum compatibility is an issue. The vendor does use epoxy to bond the semiconductor to the can, though they have not been willing to tell us what type is used. These quad diodes are currently being vacuum tested/qualified by LIGO. They have passed the RGA scanning test, and are currently in a contamination test cavity setup.

For the 532 nm beams, InGaAs gives essentially no response, so we need to use a silicon photodiode instead. Our leading candidate is the Perkin-Elmer C30845E. Again there is epoxy used to bond the silicon to the package, but PE is more forthcoming: it uses EPO-TEK H20E from Epoxy Technologies (this is a NASA approved low outgassing adhesive). These diodes will be submitted to the LIGO vacuum qualification queue. These diodes will be designed to detect a power level of 0.1-1 mW.

Vendor	Model	Material	Size	Response
OSI	Q3000	InGaAs	3 mm diam.	0.8 A/W @1064 nm
Perkin-Elmer	C30845E	Silicon	8 mm diam.	0.3 A/W @ 532 nm

Biasing. Both types of photodiodes will be operated in photoconductive mode with a small reverse bias. Since low capacitance is not important, the bias is kept small to limit power dissipation. The bias voltage for both types of diodes will be 3 V.

4 Photodiode Mounts

Figure 1 shows the mount assembly for the in-vacuum quad diode elements. The drawing for this assembly is LIGO-D1002106. The QPD is electrically isolated from the mount base. Conductive cooling is provided by sandwiching the QPD to an alumina plate, which is cooled conductively through the rest of the aluminum mount. The maximum power dissipation in the InGaAs quads is 50 mW optical plus (3V * 40 mA) electrical, or 170mW total. For the silicon diodes, it is 1 mW optical plus (5V * 0.3 mA) electrical, or about 3mW total. A conservative estimate of the thermal resistance of the QPD mount is a few 10's of °C/W, so even for the InGaAs diodes the temperature rise should be less than 10 °C.



Figure 1 D1002106: ISC QPD mount assembly. This assembly can be used for mounting either the Q3000 InGaAs quad diode, or the C30845 silicon quad diode. Different flex circuit PCBs are used for the two types of diodes, but all other parts are the same.

5 Cabling

Two of the QPD assemblies shown in Figure 1 are cabled together in pairs to make a hard-wired dual-QPD assembly, as shown in Figure 2. Standard in-vacuum 25pin-to-25pin D-sub cables are used to make the connection to the vacuum chamber feedthrough.



Figure 2 Custom cable for the dual-QPD assembly. The connector on the left is a male 25-pin D-sub. The right side of the drawing shows how the cable pig-tail wires are threaded through the PEEK back plate of the QPD assembly, where they are soldered to the flex circuit PCB. Several lengths of this type of cable assembly exist for the different in-vacuum QPD locations.

Flavors of cables used for the in-vacuum dual-QPD assemblies:

Cable drawing	Lengths	Where used
D1000231	36"	TransMon; HAM3: MC2 Trans
D1101654	40"	HAM6: OMCR_A/B & AS_C; HAM2: SM2 Trans & ISS
D1101624	68"/80"	HAM3: POP_A/B

6 Transimpedance Amplifier

6.1 Readout requirements

The alignment control system requires the TransMon Quads to give shot-noise limited signals at frequencies above 10 Hz. At full interferometer input power (125 W), the TransMon optics will be arranged to give up to 50 mW on each TransMon Quad, which is the maximum power we are confident the photodiodes can operate at continuously. We may choose to initially set up the TransMon optics with a greater transmission to the quads, so that the 50 mW level is reached at a lower input power. In any case, the readout is designed so that electronics noise is at least a factor of 4 below shot-noise with 50 mW on the photodiode. This means that shot-noise will dominate the output over approximately a factor of 10 of the input power range. Furthermore, since the readout amplifier is external to the vacuum, better signal-to-noise at the low power end can always be achieved by changing the transimpedance value in the amplifier.

6.2 Amplifier specifications

- i. Reverse bias for photodiode: 3.0 V
- ii. Detector noise is to be limited by shot noise for currents in excess of 1mA photocurrent
- iii. Signal whitening included as appropriate
- iv. Differential outputs
- v. Transimpedance 1000 ohms (not including the differential driver gain)
- vi. Full Scale Photocurrent (per segment) 10 mA (produces 10 VDC)
- vii. DC Supplies: +18VDC, -18VDC
- viii. Interface Connectors Input: One 25 pin D-Sub; Output: One 25 pin D-Sub

6.3 Transimpedance Amplifier Design

A block diagram of the QPD transimpedance amplifier is shown in Figure 3. The actual schematic is found in <u>LIGO-D1001974</u>.

The 4 identical channels of the readout circuitry use a true current-to-voltage (I to V) converter topology with negligible input impedance at audio frequencies. The nominal transimpedance is 1000 ohms, but other values can be used as desired. A single stage of whitening is included consisting of: DC gain of 1, one zero at 0.4 Hz and one pole at 40 Hz. This level of whitening is sufficient to ensure all signals down to the noise limit of the detector are transmitted at a level of at least 100nV/rtHz at frequencies of ~0.5 Hz and above. A fully differential output driver stage is used to transmit the output signals.

Since the photodetector is located in the vacuum system, with several meters of cabling between it and the front end amp, a sense wire is used to cancel the noise picked up on the wiring as the photocurrent is transported to the transimpedance amplifier. This was the technique used in the eLIGO OMC. This sense channel does add some additional electronics noise on each diode channel; however, since this sense channel noise is the same in each diode channel it is subtracted out of the actual alignment signals produced by the quad detector (it does remain in the sum channel). Starting with v5 of D1001974, the circuit includes a sum output: the outputs of the 4 transimpedance stages are summed together and sent to a rear panel BNC.



Figure 3. Block diagram of the QPD transimpedance amplifier, showing one of four channels, and the sum output.

6.4 Amplifier chassis

The assembly drawing for the QPD transimpedance amplifier is <u>LIGO-D1002481</u>. Since two QPDs are cabled together into a single 25pin D-sub connector, this is a dual amplifier chassis that serves both QPDs. The chassis contains 2 transimpedance amplifier boards (previous section), and an interface board to split the input to the two amp boards.

6.5 Transfer Function

Figure 4 shows an overlay of the simulated and measured transfer function. In order to make the measurement simple, a 1k resistor was tacked onto the input to U1. The result of this is to divide the total gain by 1000 as reflected in the annotation. The true gain is 60dB higher than plotted at the single ended output depicted in figure 1. An additional 6dB of gain will be present (not shown in figure 2) if one includes the differential driver gain.



Figure 4 Transfer function of the transimpedance amplifier shown in Fig 3.

6.6 Noise

Figure 4 shows the simulated differential output noise of a single channel of the circuit in D1001974.



Figure 4 Output noise of a single channel of the QPD transimpedance amplifier (simulated). The noise plateau around 100 Hz is $1.3 \,\mu V / \sqrt{Hz}$.

Input Referred Noise of As-built aLIGO ISC OPD Amplifier 1.85 1.86 1.75 1.75 1.75 1.75 1.65 1.

Figure 5 plots the DC photocurrent for which shot noise would be equal to the input referred current noise of the transimpedance amplifier.

Figure 5 Input referred current noise of a single channel of the QPD transimpedance amplifier, expressed in terms of the DC photocurrent for which the shot noise is equal to the input current noise. I.e., at this level of photocurrent, the SNR for shot noise is unity.

Finally, Figure 6 plots the same equivalent photocurrent, but for the SUM output and the PITCH (vertical motion) output of the amplifier; the latter is in reality formed digitally from the sampled output of the four channels. Note that in the four channel quadrant detector electronics, the additional electrical noise injected by the noise cancellation amplifier is applied in common mode to each channel. This additional electrical noise is present in the SUM channel, but is subtracted in the calculation of PITCH and YAW. This explains why the equivalent photocurrent is lower for the PITCH output than the SUM output.



Figure 6 DC photocurrent for which shot noise equals amplifier input current noise for the SUM output of the transimpedance amplifier, and also a calculated PITCH output. The noise introduced by the noise cancellation circuit is coherently subtracted in the PITCH output, but coherently added in the SUM output. This explains why the PITCH (SUM) noise current is lower (higher) than 4 times the individual channel noise shown in **Figure 5**.