LASER INTERFEROMETER GRAVITATIONAL WAVE OBSERVATORY
- LIGO -
CALIFORNIA INSTITUTE OF TECHNOLOGY
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Technical Report	**LIGO-T960038 - 00-I**	3/22/96	

LSC Photodetector Development

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Distribution of this draft:

ISC Task Group

This is an internal working note
of the LIGO Project.

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1 ABSTRACT

This note summarizes some technical considerations in design and specification of LIGO Length Sensing and Control (LSC) photodetector units. Exploration of InGaAs photodiode technology is proposed. Tests are proposed to address specific technical concerns, with a view toward adopting a basic optical and electronic configuration early. This is intended to permit parallel engineering while proceeding with more detailed noise-related investigations.

Keywords: Photodiode, LSC, photodetector, saturation, quantum efficiency, InGaAs

2 BACKGROUND

The four independent interferometric degrees of freedom in the LIGO power-recycled interferometer are derived from radiofrequency (RF) photocurrents detected by three photodetector units. Independent degrees of freedom are separated by demodulating (homodyning) each of the photocurrent signals at two orthogonal RF phases. To meet the LIGO interferometer sensitivity goals while maintaining a practical implementation of other systems, these detectors must have a number of special capabilities:

- high quantum efficiency at 1.06 micron wavelength
- no degradation in SNR up to 400 milliamperes^{TBR} of steady-state photocurrent
- high linearity and uniform RF response at this level of average photocurrent
- robustness against brief power transients (up to ~ watts^{TBR} for ~ milliseconds^{TBR})
- negligible electronic noise compared to the shot noise in detected photocurrent
- high dynamic reserve
- high spatial uniformity in RF response
- compatibility with operating frequencies between 20 and 80 MHz (baseline: 37 MHz^{TBR})

LIGO will develop and engineer custom detector units, since units having these properties are not available commercially.

3 BASELINE CONCEPTUAL DESIGN

3.1. Scope and context

Each photodetector unit includes:

- photodiode sensor(s)
- electronics to provide reverse diode bias
- electronics to filter and amplify the RF photocurrent for driving cables and balanced mixers
- electronics to read out the average (DC) photocurrent
- electronics to implement overload/overcurrent protection (as required)
- electronics to control gain and allocate dynamic reserve (as required)
- electronics to test and calibrate the unit
- a controllable incoherent light source for end-to-end LSC system shot noise tests

The optics needed to relay the sensed laser beam out of the vacuum system, match its diameter and shape to the photodiode active area(s), and divide the beam among multiple sensing elements (if required) are *not* included in this scope, although they must clearly be included in any design evaluation. Also excluded are the demodulation systems which process the RF detector outputs, and any user control and operator interface provisions.

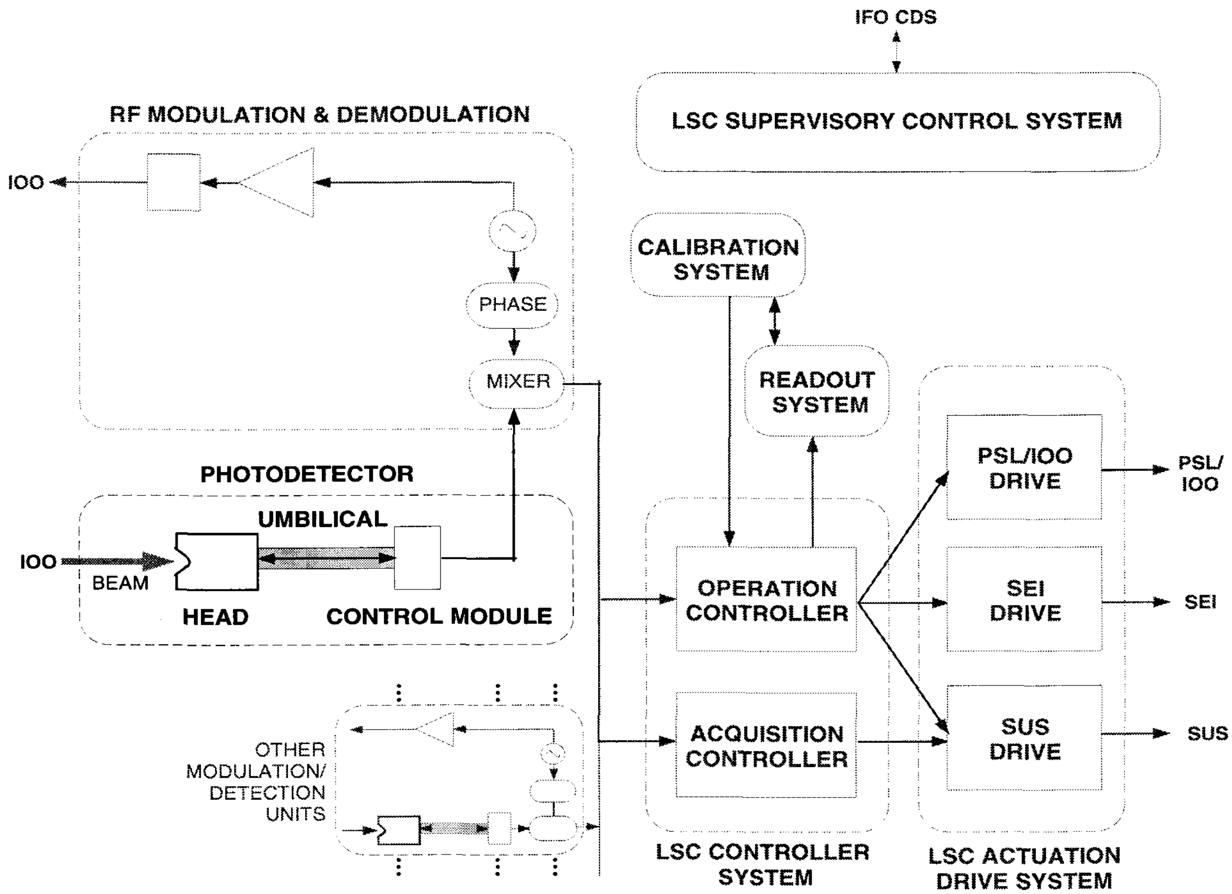

Figure 1: LIGO LSC subsystem block diagram and interfaces. One of the three photodetector units is shown highlighted (others have comparable interfaces, as indicated schematically in the inset). Key: LSC = length sensing/control, PSL = prestabilized laser, CDS = control and data system, SEI = seismic isolation, SUS = suspension, and IOO = input/ output optics. LSC Supervisory Control provides operator and internal configuration interfaces to each component (not shown).

Functions of each detector unit are distributed between a remote head, which will be located adjacent to LIGO Vacuum Equipment laser beam I/O ports in the Hanford and Louisiana Corner Station LVEA's, and a control and interface module located in a nearby electronic equipment rack. The control and interface module will be built in a 6U VME format or equivalent, while the detector head will have a custom RF-shielded housing. They will be joined by umbilical cable bundles (mixed 50 ohm coax and multiconductor in a common shield) about 10 meters^{TBR} in length. For a view of how the detectors fit within the scope of the LIGO LSC system, refer to Figure 1.

3.2. Diode selection

To date, silicon PIN photodiodes have been used LIGO interferometer prototypes operating with the 515 nm Argon ion laser line. However, even IR-enhanced silicon devices have relatively poor quantum efficiencies (of order 50%) at 1060 nm. Also, space charge saturation, power dissipation and damage effects appear to limit their tolerable photocurrent density to 20 mA/cm^2 or less. Standard "large area" Si PIN diodes like those used in LIGO prototypes (for example, the EG&G SGD-444 and DT-110) could thus each take about 1/20 the required steady-state flux. The optical and electronic implications of dividing the beam power among as many as 20 individual diodes are formidable, and the resulting implementation would be undesirably complex, cumbersome and costly.

As a result we are reluctant to use silicon. At the moment the best candidate appears to be InGaAs, which promises significantly greater quantum efficiency (85% or better) and much higher current density per unit area (1 A/cm^2 has been advertised). While these are obviously attractive features, at least two difficulties need to be addressed:

- Production and characterization of devices in this material have not advanced to the same maturity as for silicon. In particular, large-area (> 3 mm diameter) devices are only recently becoming available.
- LIGO has no experience using these devices in sensitive interferometers. For example, detecting the weak RF signal photocurrent in the presence of large noise currents at other frequencies and modal interference through spatial nonuniformities in the quantum efficiency present significant concerns.

We hope to address some of these concerns during the LSC preliminary design phase by testing prototype detector systems, as discussed below.

3.3. Head layout concept

Although the optical design of the matching and dividing optics formally lies outside the LSC scope of work, it must be considered an intimate part of the head configuration. Among other things, the external optics must accommodate:

- number of physical diodes
- angle of incidence on each diode (e.g. provide anamorphic imaging if angle is large)
- diode diameter and allowable peak power density
- equal optical path (tolerance TBD) to each diode element from interferometer optics
- minimization of backscatter
- TV monitoring of spatial intensity distribution

These factors are highly dependent on the precise choice of photodiode, and therefore early work to choose a baseline device has very high priority. In addition, the head's remote location and critical SNR subjects it to significant RFI, ground loop and antenna problems which must be accomodated by careful package design. A schematic package concept addressing some of these requirements is depicted in Figure 2.

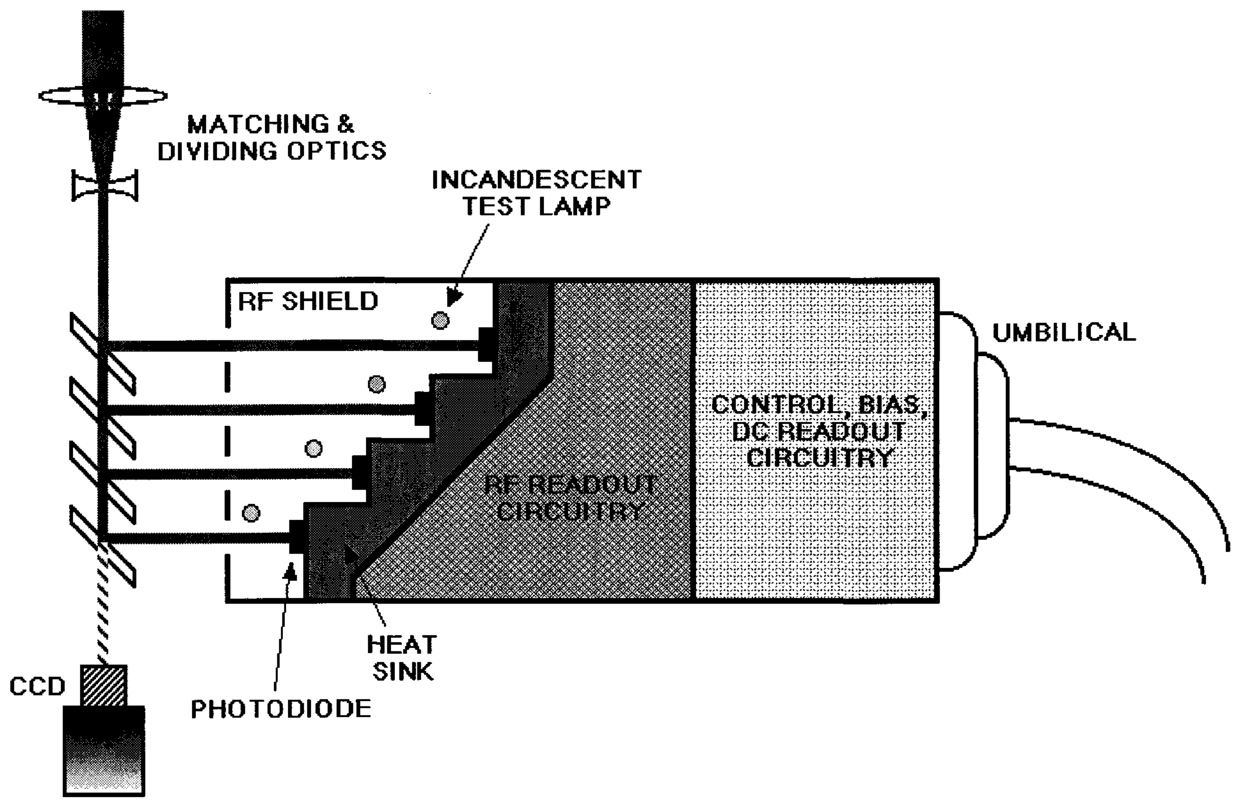

Figure 2: Photodetector head layout concept (four diodes shown, actual number TBD). Matching & dividing optics and CCD fringe monitor camera, while formally outside the LSC work scope, must be designed in conjunction with head. Subdivided enclosure provides isolation of sensitive RF components from other circuitry. Stepped detector placement is intended to maintain identical optical path from interferometer to each detector surface. This simplifies beam imaging and mitigates potential scattering and spatial mode fluctuation noise mechanisms. Possible angled placement of diodes (to improve quantum efficiency and reduce backscattering) and associated anamorphic imaging components are not shown explicitly.

3.4. Electronics concept

Radiofrequency photodetector circuits used in LIGO prototypes have typically been of the form depicted in Figure 3. An inductor is tuned to resonate with the diode junction capacitance[1] at the working frequency. A low-noise preamplifier (with noise impedance matching the resonant impedance of the diode tank circuit) drives the 50Ω double-balanced mixer. The effective shunt resistance of the diode itself (Figure 4) is a critical parameter in the system SNR and dynamic reserve; this may vary by significantly between devices of the same nominal type. This effective shunt is generally much lower and less controlled than the DC leakage impedance usually specified by the manufacturer, and depends somewhat on operating frequency.

Frequently the dynamic reserve of the system as a whole is constrained by the maximum signal level accepted by the mixer. As a result high preamplifier gain is not generally admissible (at least for lock acquisition, where there are large RF transient signals). Detectors in the 40 meter prototype have had voltage gain $A_{RF} \sim 1$ and LC circuit effective impedances of 0.5 -2 kΩ at resonant operating frequencies around 10 MHz.

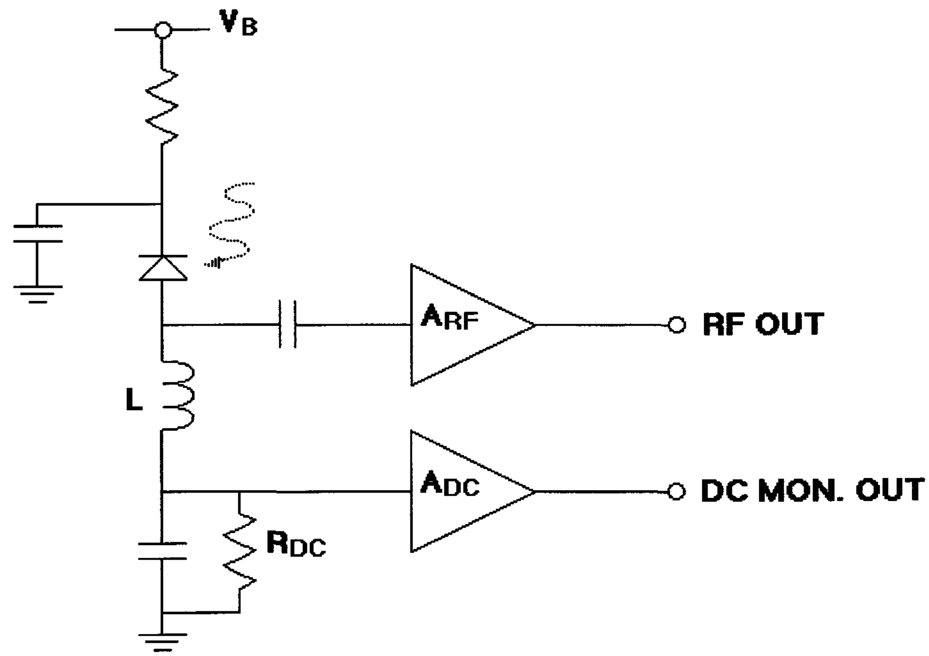

Figure 3: Conceptual schematic of individual photodiode readout circuit. Inductance L is chosen to resonate with junction capacitance of photodiode at working frequency. Not shown are additional bandpass filters and notch traps for harmonics of the modulation frequency, usually included in the RF amplification stage.

LIGO will use higher operating frequencies (around 40 MHz), and InGaAs diodes will generally have higher C and lower effective shunt impedance per unit area (at admissible reverse bias volt-

1. of order 100 pF for typical 1 cm^2 Si PIN diodes reverse-biased at 150 volts

ages). Although they may have less total capacitance per unit *power* accepted, it may be still more difficult to match these detectors to available preamplifiers. Nonetheless, at the higher photocurrent levels envisioned, simple broadband transimpedance stages (e.g. just a load resistance and preamplifier) may be appropriate.

The diode electrical parameters will also determine the optimal way to combine diode outputs. Electrical addition of RF preamp outputs from individual circuits like that shown in Figure 3 would be the most straightforward implementation, but impedance matching and SNR considerations may require photocurrent addition prior to active stages (e.g. using transformers to achieve the equivalent of a "series" connection, to increase the effective noise impedance).

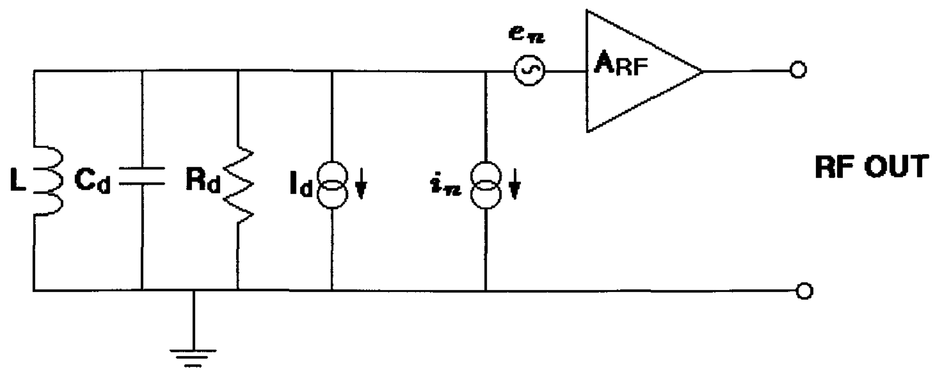

Figure 4: Radiofrequency equivalent circuit. Effective photodiode junction capacitance C_d and shunt resistance R_d may depend on photocurrent I_d, leading to intermodulation. e_n and i_n are voltage and current noise of RF preamplifier, respectively.

3.5. Overload Protection

The stored circulating power inside the recycling cavity of an operating LIGO interferometer will be over 100 W. Loss of length control during operation will momentarily permit some of this power to appear at the dark (antisymmetric) port, temporarily subjecting the photodetectors to severe overload conditions. The amplitudes, durations and waveforms of these power transients depend on the detailed optical and mechanical behavior of the interferometer, and are currently being modeled numerically. In any case it is evident that a combination of robust design and explicit protection mechanisms will be necessary.

Electromechanical shuttering may be too slow to afford adequate transient protection, and electrooptic or acoustooptic shutters will introduce undesirable optical losses, limiting the effective quantum efficiency. Each of these will also be cumbersome and costly to engineer. It is hoped that instead a combination of robust device selection, conservative thermal design and fast-acting electrical protection can prevent damage.

This electrical protection may take the form of a fast crowbar on the detector's reverse bias. In the reverse-biased condition (required for bandwidth and linearity in operation) an InGaAs junction may dissipate an order of magnitude more heat than with bias removed. As a result it is important to establish not only the damage threshold and overload withstand time under biased, operating conditions, but also with the bias removed (or reduced) to simulate such a "protection" mode.

4 TEST PROGRAM TARGETS

As indicated, strategic testing is needed both to validate expected performance models and to enable optical and electronic preliminary designs. Four phases of testing are envisioned:

1. InGaAs feasibility studies, selection of candidate manufacturers and devices
2. Preliminary tests on candidate devices:
   - power handling/damage threshold (biased & unbiased)
   - linearity & RF gain compression vs. DC power
3. Refined device tests:
   - RF intermodulation vs. DC power
   - spatial uniformity (RF and audio)
4. Integrated prototype testing on LIGO PNI facility

The preliminary tests (phase 2 above) will be designed to focus on early determination of critical parameters strongly affecting the matching and forming optics (LIGO IOO) and the electronics (LIGO CDS) design activities. For example, it is anticipated that diode number, diameter, and angle of incidence will be provisionally adopted at the end of this phase, as will current per diode, bias voltage and protection requirements.

The third testing phase would proceed in parallel with electronic and optical design, to determine parameters related to expected noise processes. In general these explorations are expected to have less impact on system optimization (though significant findings may still have serious repercussions). They are expected to illuminate interactions with scattered light, spatial mode quality and laser amplitude noise. A conceptual schematic of a test setup suitable for preliminary and refined tests of this nature is shown in Figure 5.

Finally, we plan to perform integrated testing of an advanced detector prototype on the LIGO PNI (Phase Noise Interferometer) facility during and after its conversion to 1.06 micron wavelength operation. These tests will explore noise processes in detail, and permit operational verification of basic operation and SNR characteristics.

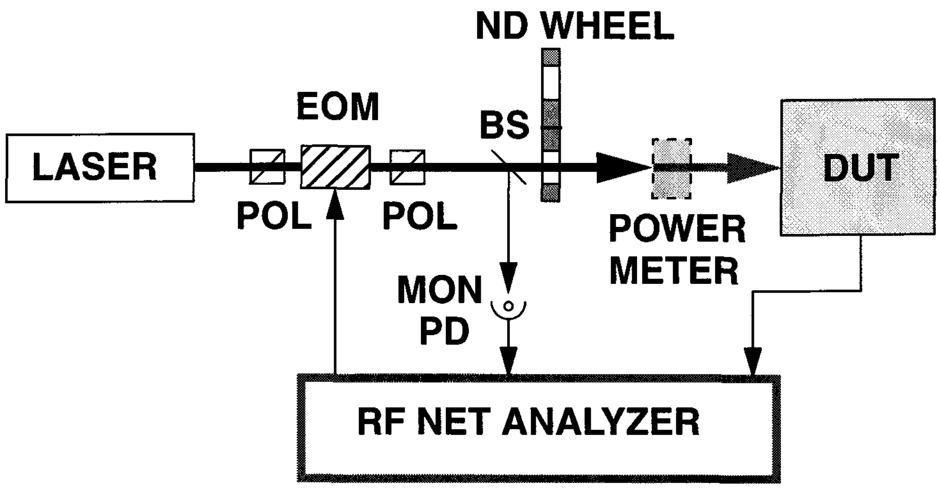

Figure 5: Schematic of photodiode/photodetector unit testing setup. Light from diode-pumped 1060 nm solid state laser (500 mW class) is amplitude modulated by an electrooptic modulator (EOM) between crossed polarizers (POL). The diode under test (DUT) may be mounted on XY translation mounts to investigate spatial nonuniformity. Not shown are lenses to achieve the desired beam profile at the diode surface, and a beam scanning instrument needed to establish and periodically verify this profile. Neutral density (ND) filters just ahead of the DUT permit variation of power without affecting laser or EOM spatial and temporal characteristics.

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