New Folder Name Analog Visibility Monitor

Analog Visibility Monitor and Cavity Resonance Discriminator

M. E. Zucker

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Abstract

To optimize the coupling efficiency of a laser beam to an optical cavity, experimenters must often calculate the ***visibility*** of the interference, that is, the fraction of incident laser power which passes into the cavity rather than being reflected. A simple analog instrument is described which automates this calculation in real time. The instrument also provides a logic signal indicating whether the cavity is in resonance; the decision threshold may be set at a visibility which discriminates against off–axis modes of the cavity, permitting (with additional circuitry) automatic and exclusive recovery to the TEM_{00} mode after a disturbance.

1 Theory and Application

Consider the example stabilized laser system shown in Figure 1. The wavelength of the laser is servo–controlled to resonate with the optical cavity formed by mirrors M1, M2, and M3 by use of a phase modulation reflection–locking technique [1]. To optimize the signal–to–noise ratio of the resonance detection, and (where applicable) to optimize the transmission of optical power through the output coupler M2 of the cavity, the wavefront parameters of the laser beam must be optimally matched to those defined by the cavity mirror separations, curvatures, and orientations [2]. In one limiting case, where the transmission of M1 is precisely matched to the sum of all other transmissions and losses of the cavity, the internal resonant cavity field

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transmitted toward photodetector D1 can be equal in magnitude and opposite in phase to the incident laser field promptly reflected by M1 (i.e., perfect destructive interference) and there will in fact be no light falling on D1 at resonance. This condition, with visibility $V = 1$, can only be obtained if the mode parameters of the laser and the reference cavity are precisely matched by choice and adjustment of lenses L1 and L2 and the orientations of the mirrors M1-3. In most real laboratory situations the mirrors are not matched, and so even for perfect alignment there will some net power falling on D1, but it is generally true that this power will reach a minimum for optimal alignment and mode–matching.

Proper alignment of the cavity is generally obtained by iterative adjustment of the mirror angles and lens positions in order to minimize the reflected light falling on D1. During this procedure, however, it is common for the incident laser power to drift, causing convergence to a false minimum. It is therefore necessary to monitor the incident laser power (for example, with diode D2 exposed to a small sample of the laser output diverted by beam sampler BS) and scale the reflected power by the appropriate factor. One may simply measure both values simultaneously and manually calculate the quotient between adjustments, or one may be rather more sophisticated and either a) servo–control the laser power to maintain a fixed "denominator" on diode D2 or b) have a computer monitor both signals, calculate the quotient, and display the results in an accessible form. The device described here involves less external apparatus than either a) or b), but maintains the advantages of accuracy and convenience and, for many purposes, is superior in terms of speed.

By observing the outputs e_1^{nr} and e_2^{nr} of diodes D1 and D2 when the cavity is away from resonance[1] it is possible to determine the scaling factor α such that $\alpha e_2^{nr} = e_1^{nr}$. Then, by use of suitable differential amplifiers and a high–speed analog divider circuit, the device provides a continuous monitor of

$$V = \frac{\alpha e_2 - e_1}{\alpha e_2} = \frac{I_{inc} - I_{refl}}{I_{inc}},$$

that is, the *visibility*, where I_{inc} is the incident laser power on M1 and

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[1] This can be arranged by suitable adjustment of the laser wavelength to lie between cavity modes, by blocking or misaligning one of the cavity mirrors, or by disabling the wavelength servo so the laser is out of resonance.

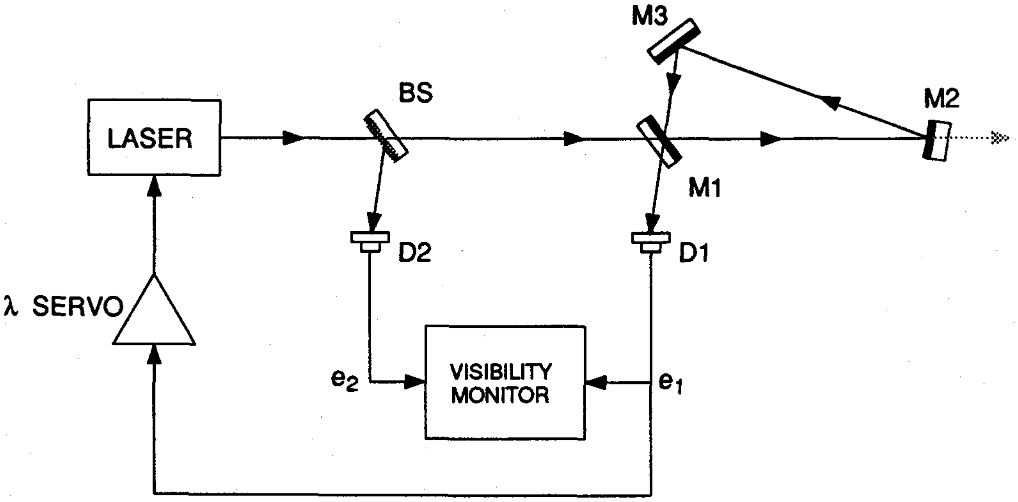

Figure 1: An optical cavity used as a reference cavity for laser wavelength stabilization. In this example, the laser's wavelength is controlled in response to a phase error signal derived from the output e_1 of photodetector D1. The phase modulator and electronics required to derive this signal are omitted for clarity. A beam sampler (BS) directs a fraction of the incident laser power onto reference detector D2; the output e_2 of this detector is fed into the Visibility Monitor along with e_1. A triangular cavity is shown, although application to two-mirror and other cavity geometries is equally appropriate.

I_{refl} is the reflected power falling on D1. The visibility is displayed on a panel meter and is made available as a scaled analog voltage for recording purposes.

In many reflection locking schemes with non–confocal cavity geometries [2] it is possible for the laser system to lock to any of several spatial modes of the cavity, all of which define slightly different wavelengths. The TEM_{00} spatial mode is generally preferred, since it is best matched to the typical laser beam and thus provides the best signal–to–noise ratio and (where required) the best cavity throughput. The propensity to lock in off–axis spatial modes is thus often frustrating. Once a cavity has been properly matched and aligned to its input beam, however, the visibility of the TEM_{00} will usually be significantly greater than that of other competing modes, allowing convenient discrimination. By comparing the computed visibility with a user–defined "threshold" visibility, the device provides a convenient logic output which can be used, for example, to disable the servo for all but the TEM_{00} cavity mode, to actively hunt for the proper mode by scanning the laser until it is found, or simply to record for the experimenter when unlocking has occurred. The speed of the thresholding decision is in principle limited only by the optical storage time of the cavity, making it possible to clearly discern even very short–duration dropouts which might otherwise escape detection. The logic output is available directly and can also be gated by an external logic input. This can be used, for example, to enforce the condition that one cavity servo be locked before another is engaged in a multi–cavity arrangement.

2 Circuit Description

Referring to Figure 2, Appendix C, the cavity reflection detector and external reference detector signals are processed by identical variable–gain preamplifiers U1 and U8. The option of omitting the external reference detector and substituting Zener reference CR5 is provided by panel switch SW1, for use when no external reference detector is available. Both inputs are protected by 500Ω series resistors and diode bounds to the power supply rails. Inverter U9 allows the circuit to be used with cavity reflection photodetectors whose outputs are either positive– or negative–going. This feature is provided because the cavity reflection detector is often optimized for RF performance or some other criterion, and thus one often has no choice of biasing direction. The reference detector output must be positive and must increase from zero volts with increasing power. Low "dark" output offset and high linearity are desirable for both detectors. The preamplified detector signals are viewable on the panel meter for setting up gain and checking dark levels. A $\pm 50\mu$A jeweled analog meter is used; an auxiliary scale registering from 0 (left) to 100 (right) is provided. Unipolar voltages, like the detector signals and the visibility, are viewed on the auxiliary scale by subtracting a 50μA bias current (R101, R102, and R103) and scaling to 100μA full scale.

The reference level is scaled by 10–turn vernier potentiometer R99 in order to make the out–of–resonance voltages representing the two detected powers precisely equal. This brings the outputs of differential amplifiers U3 and U10 to zero; for setup, the output of U10 is available to the panel meter in three "reference nulling" ranges offering different sensitivities. In this mode the bipolar meter scale is used. The appropriately scaled reference, buffered by U2, is fed into the analog divider circuit U4 as "denominator," and the output of difference amplifier U3 (= scaled reference minus cavity reflection) is provided to U4 as "numerator." The divider used here (an Analog Devices 535J) produces an output $e_{out} = 10.0\text{V} \times e_{num}/e_{den}$, so the output is scaled by $10\text{V}/100\mu\text{A} = 100\text{k}\Omega$ and added to a fixed -50μA bias current. This gives a full–scale deflection corresponding to visibility of 0% to 100% . The visibility output signal of U4 is also buffered by U5 (augmented by high–current driver U6), to drive a low–impedance output for recording or monitoring purposes.

Amplifier U13 also provides an output for monitoring anything which is displayed on the meter, converting the meter current into a voltage through its $100k\Omega$ feedback resistor. In addition, U13 provides overcurrent protection for the meter movement by shunting current through Zener diodes D7 and D8 if the meter current exceeds 70μA or so in either direction. Overload conditions like this can occur easily during the Reference Nulling procedure.

The scaled reference voltage is simultaneously fed to the CCW terminal of 10–turn potentiometer R100. The wiper voltage is the fraction $1 - f$ of the reference voltage, where f is the fraction displayed on RXthresX 's counting dial. This threshold standard is provided to comparator U11, which compares it with the cavity detector signal such that when the cavity detector signal exceeds $1 - f$ of the reference, U11's output is "high," that is, the cavity is deemed "unlocked." The comparator is driven directly, rather than by the analog divider, for maximum speed and to minimize the need for additional voltage references; this may sacrifice some absolute threshold precision due to the comparator circuit's built–in 5mV hysteresis. Q2 drives a panel LED indicator, and gate U7a allows an external TTL "high" input to disable the 50Ω buffered output of U12d.

3 Setup, Adjustment and Use

3.1 Establishing Inputs

Although the unit may be used without an external reference detector, this will defeat the desired normalization function. An external reference detector (see Appendix D) should be provided with a beam sample which gives a DC output voltage between 50 mV and 5V under normal operating conditions. The cavity reflection photodetector should also provide between ±50mV and ±5V when the cavity is out of resonance. Both detectors should have relatively low dark offset; if the voltages available for either input fall near the lower end of the acceptable range, DC dark offsets or stray room lights may become critical.

3.2 Adjusting Preamplifier Gains

With laser light falling on both reference and cavity detectors, and with the cavity held out of resonance (by suitable blocking or misalignment of the resonator path, or disconnection of the servo electronics), observe the cavity detector signal on the panel meter by turning the meter selector switch to **pd**. Adjust the **pd gain** range switch until the meter shows between 10% and 60% deflection (that is, between 1V and 6V after the preamplifier; the meter in this mode shows 10V full scale). Verify that the meter returns to zero when the laser light is blocked; if it does not, follow the procedures detailed in §3.3 to remedy the condition. Unblock the light and make a note of the reading before proceeding.

Next, check that the **ref adj** vernier potentiometer is fullly clockwise (at maximum gain). Turn the meter selector to **ref** and adjust the **ref gain** range switch to the *smallest* gain multiplier at which the **ref** meter reading exceeds the **pd** meter reading previously noted. If the smallest such setting still gives more than 80% meter deflection, go back to the **pd** adjustment, select one range step lower on the **pd gain** switch and note the **pd** voltage, and return to the **ref** adjustment. This will insure that moderate fluctuations in laser power will not cause saturation of the internal circuitry.

3.3 Compensating for Dark Offsets

If the **pd** or **ref** meter readings fail to return to zero when the appropriate beam is blocked, establish whether the detector itself has a dark offset (use an external voltmeter to observe the detector output directly) or the visibility monitor offset potentiometer has been misadjusted (short the PD input with a cap or terminator equivalent to the detector output impedance and recheck the meter deflection). Excessive dark offset may indicate a fault in the detector or monitor circuit, and may warrant investigation. In any case, a small dark offset may be compensated by turning the appropriate **offset adjust** potentiometer on the front panel using a small screwdriver. Up to ±150mV dark offset can be accomodated in this way.

3.4 Adjusting the Reference Vernier

Turn the meter selector to **ref null** position **1** (minimum sensitivity) or **2** (moderate sensitivity) and observe the meter deflection. In this mode the meter zero is at the center of the scale; check that the needle is to the right of zero, and begin to reduce the setting of the **ref null** vernier potentiometer to bring the needle toward center. After achieving null, increase the meter sensitivity and readjust until the meter is centered at sensitivity **3** (most sensitive).

3.5 Checking Visibility

With the reference properly nulled, turn the meter selector to **visibility** and check that the meter reads 0% (left end of scale). Next, block the cavity reflection photodetector (*not* the reference detector) and check that the meter reads 100% (right end of scale). These steps will verify that the setup has been successful. The cavity may now be permitted to resonate (unblock, realign, reconnect, etc.) and the visibility will be shown on the panel meter. An analog voltage proportional to the visibility will also be available at the **visibility out** output jack as positive voltage between 0V (0% visibility) and 10V (100% visibility) for recording or remote monitoring. In the course of adjusting the mirrors and mode–matching lenses for optimum visibility, take care that neither the reference beam nor the cavity reflection beam falls partly off its respective photodetector; periodically recheck the monitor null by removing the cavity from resonance and switching the meter selector back to **ref null**.

3.6 Adjusting the Discriminator Threshold

Once the visibility monitor has been adjusted and the cavity has been aligned for resonance and locked to the laser, one can determine the visibility of the TEM_{00} resonant mode and of higher–order modes like the TEM_{01},TEM_{11} and so on. The **threshold** potentiometer can now be adjusted to any desired visibility (the two–digit counting dial ranges from 0% to 100%). In particilar, a threshold below the visibility of the TEM_{00} mode and above that of the next mode will discriminate against higher modes. The internal comparator will give a TTL "0" at the $\overline{\textbf{lock}}$ output jack only when the set visibility threshold is exceeded; otherwise the $\overline{\textbf{lock}}$ output will remain high (TTL "1") and the **unlocked** indicator LED will be lit. The TTL output can be recorded or can drive additional external circuitry which scans the laser seeking the TEM_{00} mode. It can also be employed to switch a specialized high gain servo circuit from a wide–dynamic–reserve "acquire" mode to a low–noise "run" mode automatically. In these applications it is often useful to relax the visibility threshold while making optical adjustments, so the external system will not be triggered by temporary user–induced misalignments.

A History

The initial circuit design was sketched out in rough form by M. E. Z. and the prototype, Serial No. 1, was built in breadboard form by Eric Ahrens with guidance from Steve Clark in the summer of 1986. The prototype "Contrast Monitor"[2] has been used since then in the Caltech 40m Prototype Laser Interferometer Gravitational Wave Antenna and associated experiments. Improvements and revisions leading to the design described here were worked out by Alex Dukhovny and M. E. Z. in the summer of 1990 while constructing the second breadboard version (Serial No. 2).

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[2] At that time the term "contrast" was used to refer to what is now called "visibility." The older usage is now frowned upon, the first term being typically used for a two-beam interference figure of merit $K = (I_{max} - I_{min})/(I_{max} + I_{min})$, whereas the quantity of interest for multibeam interferometers like Fabry–Perot cavities is defined as $V = (I_{max} - I_{min})/I_{max}$.

B Initial Adjustment Procedure

The following procedure prepares a new unit for operation or realigns a unit which has undergone repairs.

B.1 Required Test Equipment

- Digital voltmeter (e.g. Fluke 77) with test probes
- Variable D.C. power supply, 0–5 or 0–10 VDC
- 1 kΩ ten–turn potentiometer voltage divider
- BNC shorting caps (2) and tees
- BNC cables, adapters and test clips to connect to circuit, meter
- NIM power socket extender cable
- NIM bin and power supply

B.2 Setting Input Offsets

Remove the covers from the module. Attach the NIM power socket extender cable to the module and to the NIM bin. Short the **photodiode** and **ext ref** inputs (J1 and J2) and set both **range** switches to ×100 and the **pd pol** selector switch to $\overline{\textbf{inv}}$. Attach the DVM common to the circuit ground and turn on the NIM bin power. Adjust the respective **input offset** potentiometers to bring pin 6 of U1 and pin 6 of U8 both to $0\,\mathrm{V} \pm 20\mathrm{mV}$.

B.3 Adjusting pd and ref Zeros

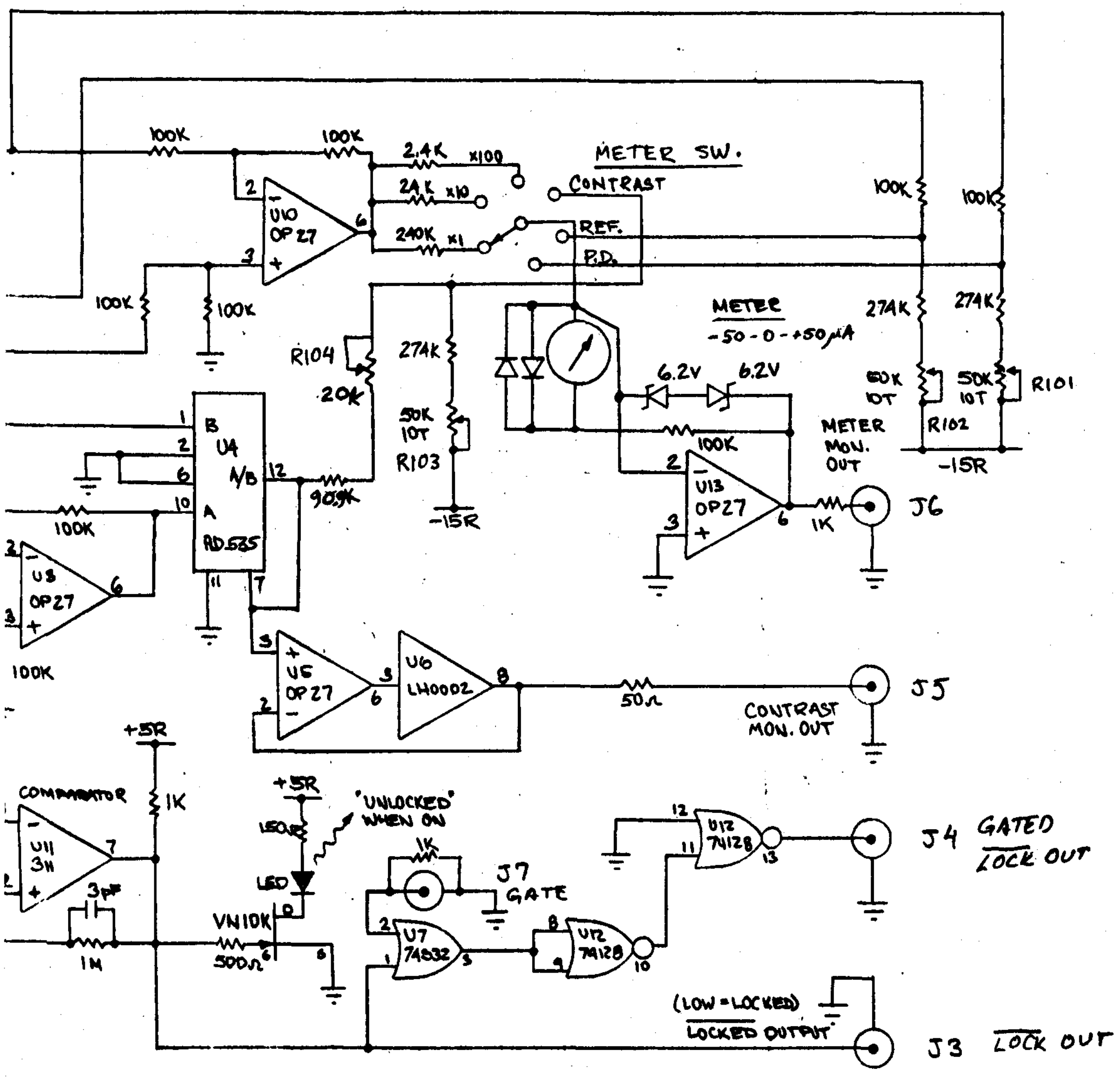
With the outputs of U8 and U1 still at zero, set the **meter** switch to **ref** and adjust R102 until the meter is at the left end of the scale (0%). Connect the DVM to J6, **meter mon out**, and refine the setting to bring the voltage to $-5\,\mathrm{V} \pm 30\mathrm{mV}$. Set the **meter** switch to **pd** and adjust R101 similarly. If the panel meter does not agree (within a small scale division) with the DVM setting, turn off all power and check that the panel meter returns to scale center; the movement may have been accidentally offset. In this case, readjust the meter movement screw and try again.

B.4 Adjusting Visibility Zero and Scale Factor

Set the variable DC supply to 0.5 V output and connect the potentiometer ends across it. Connect the DVM between wiper and power supply ground and adjust the potentiometer to give 50 mV. Connect this voltage across to *both* **ref** and **pd** inputs. Check that pin 6 of both U1 and U8 are at about 5 VDC. Now, turn down the **pd range** switch to ×30. Turn the **meter** switch to **ref null** position **1** and adjust the **ref null** vernier potentiometer R99 to bring the meter needle to the scale center; repeat on position **2** and finally position **3**. Check the voltage at J5, **Visibility Out**; it should read $0\,\mathrm{V} \pm 30\mathrm{mV}$. Attach the DVM to J6, **Meter Mon. Out**, and adjust R103 until the DVM reads $-5\,\mathrm{V} \pm 30\mathrm{mV}$ as before. Now, remove the test voltage connection to J1, **photodiode input**, and short the connector again. Check that U1's output again returns to zero volts using the DVM. Reattach the DVM to J6 and adjust R104 until the DVM reads $+5\,\mathrm{V} \pm 50\mathrm{mV}$. The panel meter should now be at full scale as well.

C Schematics and Diagrams

Figure 2: Schematic of the Visibility Monitor and Lockup Discriminator electronic circuit.



MARKS

NTEGRATED CIRCUITS RUN
5R SUPPLY AND HAVE .1μF CAPACITORS
PLY PINS

ESISTORS ARE 1%

NUSED LOGIC GATES ARE GROUNDED
HE INPUTS

IRCUIT GROUND IS ISOLATED FROM CHASSIS

CALIFORNIA INSTITUTE OF TECHNOLOGY MASSACHUSETTS INSTITUTE OF TECHNOLOGY	**LIGO** PROJECT
DRAWN B.T / R.D	VISIBILITY MONITOR AND LOCKUP DISCRIMINATOR
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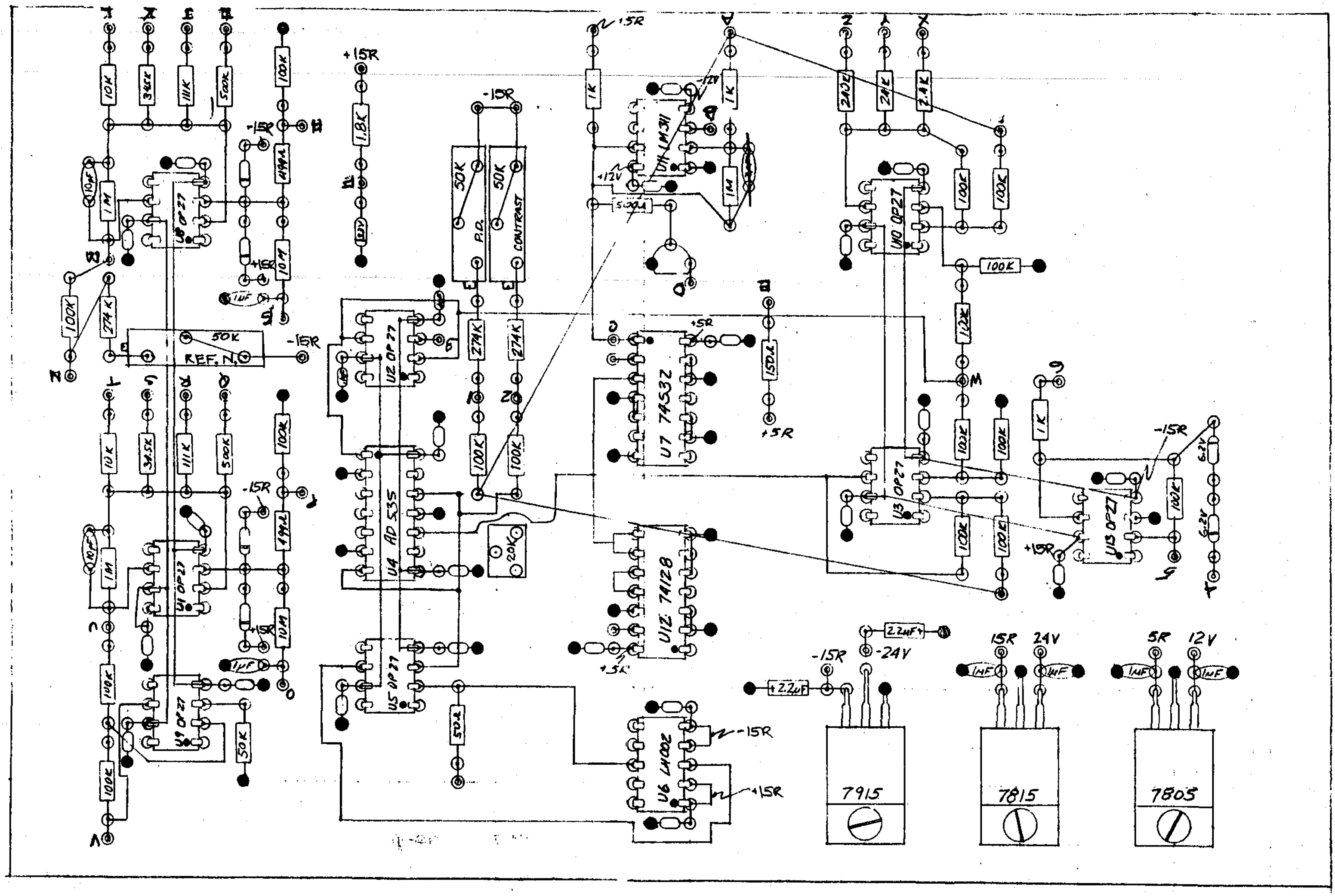
DATE 9/11/1990	DRAWING NUMBER
SCALE	SHEET 1 OF 1 REV

REV 11/12/90 MEZ

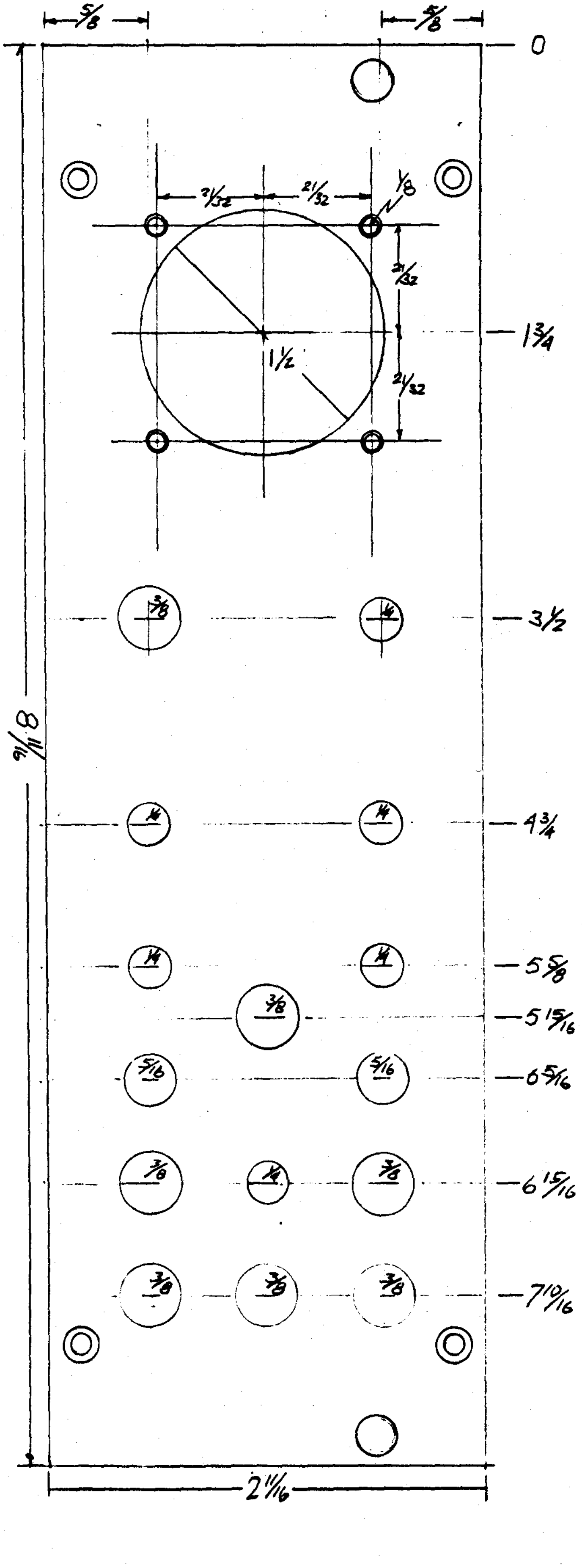
Figure 3: Layout of the breadboard for Unit No. 2. Copper–clad Vector board is used; the groundplane is left intact wherever possible, but isolated from the chassis ground and tied at a single point to the NIM power supply common. Isolated BNC connectors are used for all inputs and outputs. 1/4" standoffs hold the board on the internal rails in a Mechtronics model 201 double–width NIM module.



LOCKUP DISCRIMINATOR AND CONTRAST MONITOR

A.D. 8/9/90

Figure 4: Front and rear panel layouts and lettering for assembly in a double–width NIM module (e.g. MechTronics 201 or equivalent).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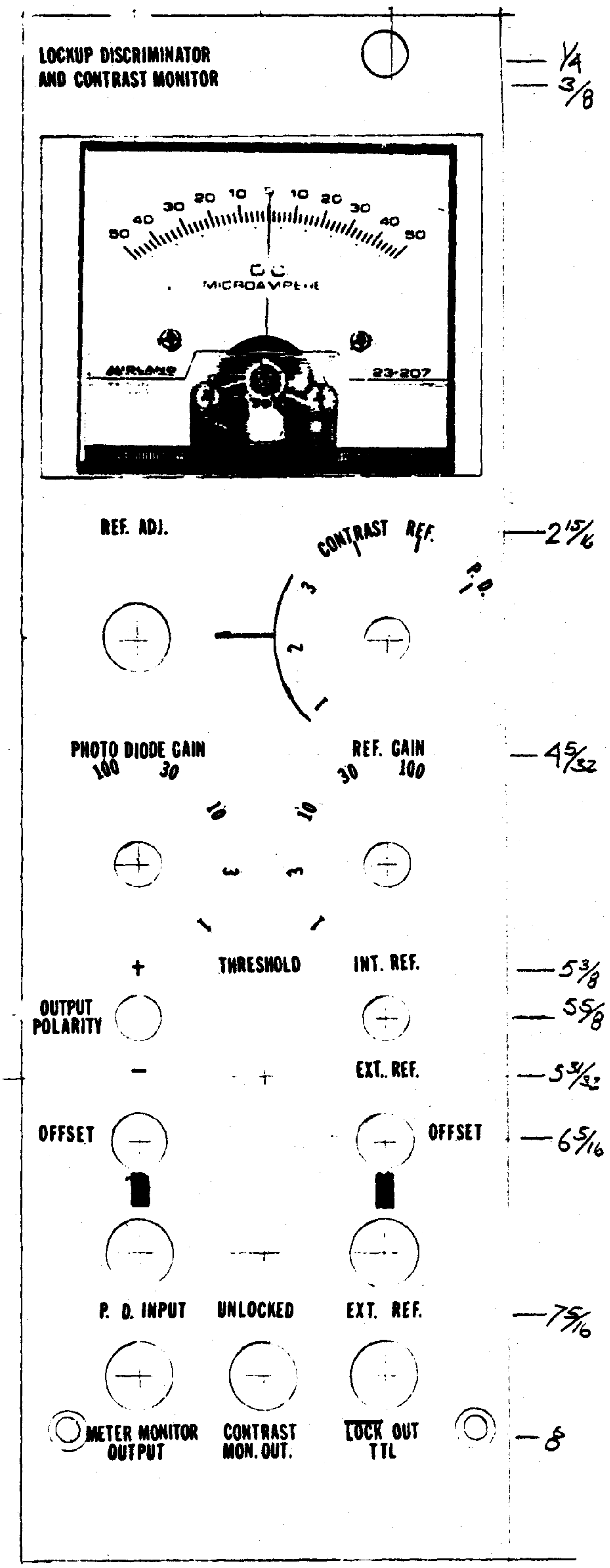
LOCKUP DISCRIMINATOR
AND CONTRAST MONITOR
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OUTPUT
POLARITY
5 5/8
-
EXT. REF.
5 31/32
OFFSET
OFFSET
6 5/16
P. D. INPUT
UNLOCKED
EXT. REF.
7 5/16
METER MONITOR
OUTPUT
CONTRAST
MON. OUT.
LOCK OUT
TTL
8

D Suggested Reference Photodetectors

Virtually any photodetector which has a positive–going DC coupled output is usable for the reference detector. We have successfully employed the following two circuits, among others.

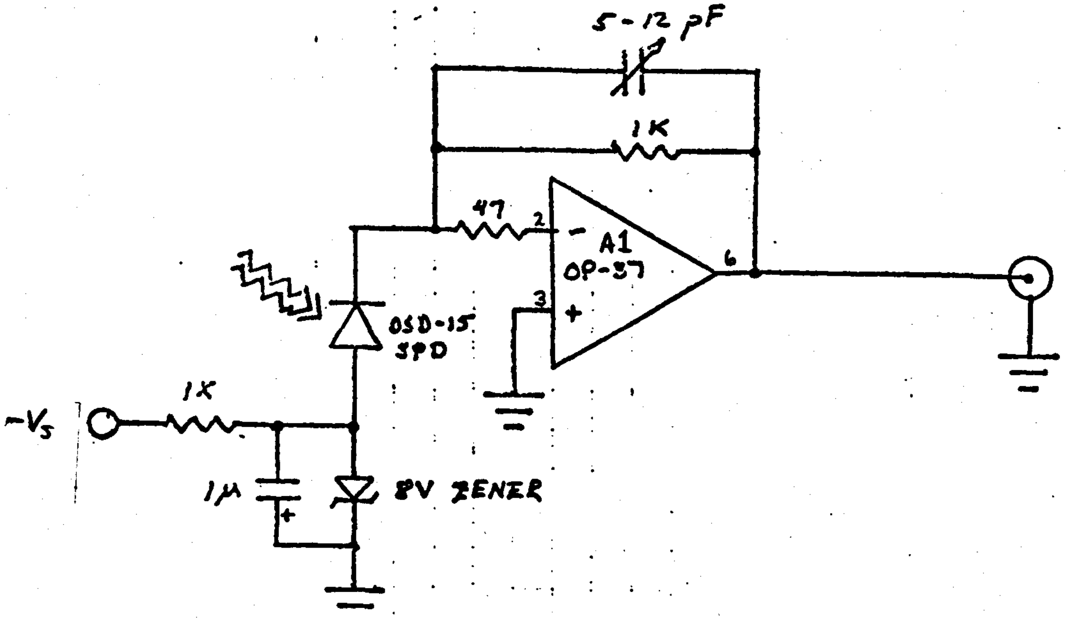
D.1 Large–Area, Medium Speed Detector

This circuit employs a fairly large area (15 mm^2) Centronics OSD–15–5T photodiode. It is fast enough (rise time of order 400 ns) to offer no limitation when used with cavities having storage times of more than a few microseconds. It also has a very low dark offset. Substituting a 10 kΩ feedback resistor and an LF356 op amp for the 1 kΩ resistor and OP–37 will give a more sensitive detector with somewhat degraded risetime.

Figure 5: A simple reference photodetector for applications where risetime is not critical.

NOISE EATER SENSING DIODE   2/27/85 MEZ

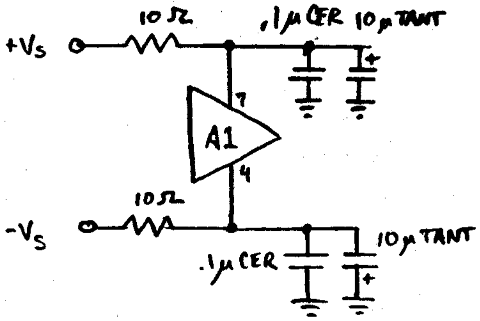
DIODE #73



OUTPUT 0.33 V/mW

DARK NOISE ≈ 5 nV/$\sqrt{Hz}$ (TYP.)

SUPPLY DECOUPLING



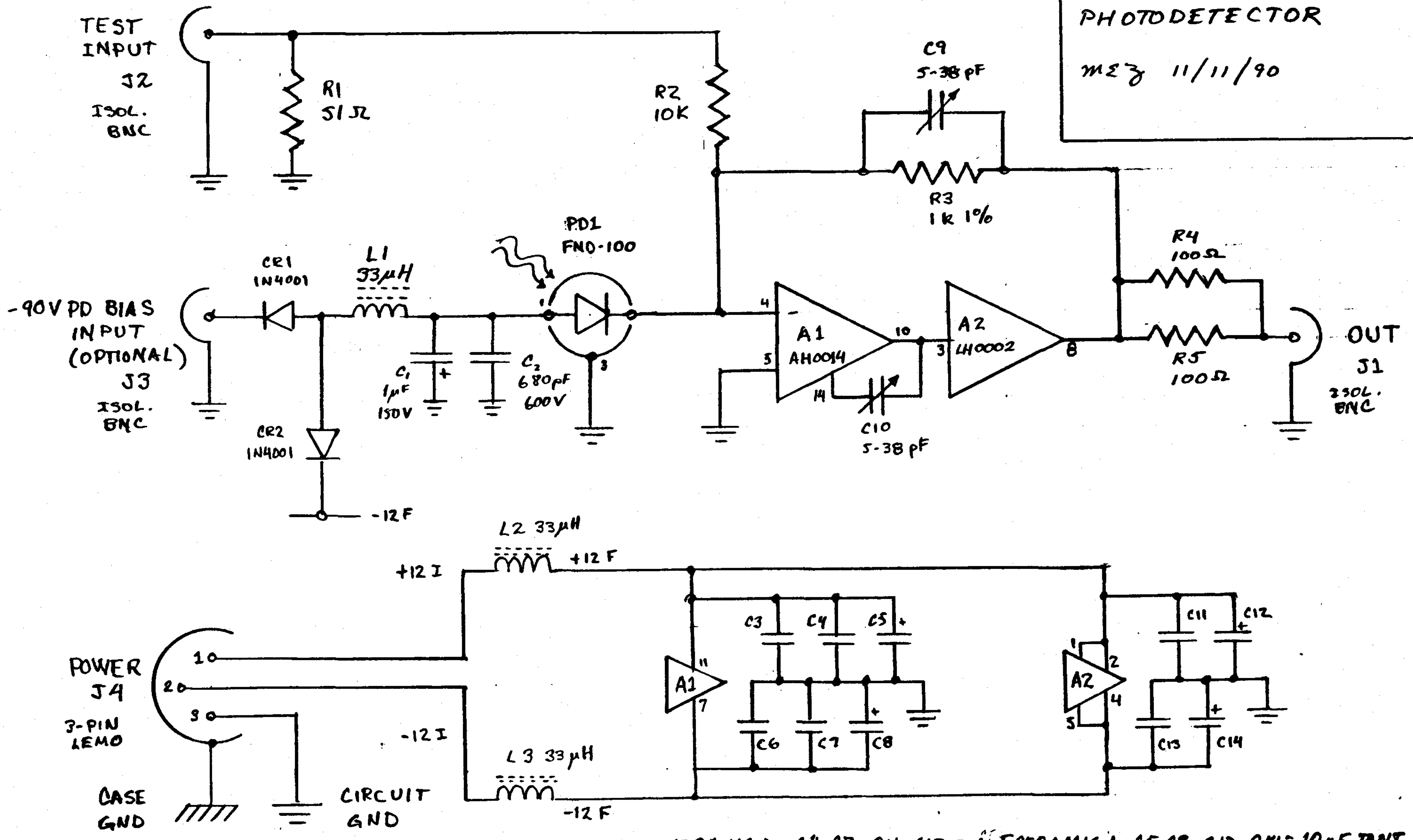
D.2 Fast Reference Detector

This detector is normally used in the Caltech LIGO prototype lab for measuring cavity storage times by the ringdown technique [3]. C9 and C10 should be trimmed for rapid settling and minimum overshoot by injecting a square wave at **TEST INPUT** J2. C10 must also be adjusted to avoid oscillation with capacitive loads up to 0.1 μF across **OUTPUT** J1. To achieve optimum rise time, connections to pins 4 and 5 of A1 should be as short as possible. Use of a ground plane circuit board and power supply decoupling as shown are essential. Rise and fall times $t_{10-90\%} \approx$ 18ns are achieved with this circuit. The speed is mostly determined by the amplifier, but a small improvement can be obtained by increasing the reverse bias voltage on the FND–100 photodiode to -90 VDC at J3, **BIAS INPUT**. Detector noise is equivalent to the shot noise from about 60 μA of DC photocurrent. This corresponds to about 200 μW of detected power if the FND–100 is used at normal incidence with its glass window in place.

Figure 6: A faster reference photodetector employing the popular FND–100 PIN photodiode from EG&G.

RINGDOWN
PHOTODETECTOR

mez 11/11/90



C3, C6 = .1µF CERAMIC; C4, C7, C11, C13 = 1µF CERAMIC; C5, C8, C12, C14 = 10µF TANT.

References

[1] R. W. P. Drever, G. M. Ford, J. Hough, I. M. Kerr, A. J. Munley, and H. Ward, "Laser Phase and Frequency Stabilization Using an Optical Resonator ," *Appl. Phys.* **B 31**, p. 97 (1983).

[2] A. E. Siegman, *An Introduction to Lasers and Masers.* McGraw–Hill, New York (1971).

[3] Dana Z. Anderson, Josef C. Frisch, and Carl S. Masser, "Mirror reflectometer based on optical cavity decay time," Appl. Opt. **23** 8, p. 1238 (1984).