THE FIBER OPTIC ROTATION SENSOR

A REPORT BY THE
ROOKIE GROUP

MAY 5 1984

presented to:
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by
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ABSTRACT

Sensitive rotation sensors have been made possible because of the recent development of low loss optical fibers. This project using these new low loss fibers was proposed and developed by Robert Lokuta and Teresa Moruzzi. We, the new members of the Fiber Optic Rotation Sensor team, will proceed with the construction of the space worthy system. This system is to be launched on a 1985 space shuttle flight.

INTRODUCTION

In this appendum to the veterans' final report we discuss the various changes that we have proposed for the fiber optic rotation sensor (FORS). The new or rookie team on this project has taken over the task of developing a FORS that will be fully tested and prepared to undergo the rigors of space flight. Most of the theoretical material has been covered by the veterans of this project, so we will go beyond that point in our report and apply what they have researched into building of the space-ready FORS.

We will first briefly describe the prototype and system design. Then we will cover the possible modifications such the use of one coupler instead of two, and the monitoring of the Piezo driver to detect fluctuation due to temperature. The section called "Implementation" is included in this report due to the importance of the alignment of the fiber loop in the space shuttle. Anticipated problems such as polarization, electrical and optical noise levels and sensitivity range will be discussed. Finally, we will include intended testing procedures such as the investigations of the piezo driver's sensitivity to temperature, rotating table for calibrational purposes and running the FORS for extended periods of time to check for system drift and battery life.

All figures with numbers (such as Fig. 3.1) originate from the veterans' report, and are copied in this report for the reader's convenience.

REVIEW OF PROTOTYPE

The vets' FORS is composed of six key elements (see Fig. 3.1). These elements are: one kilometer of single mode optical fiber, a 1.3 micron superluminescent diode (SLD), two 2x2 couplers, a piezo electric cylinder, a PINFet photo detector, and finally the associated circuitry necessary to run all the above components.

The SLD produced by Valtac corporation, operates at a wavelength of 1.3 microns and at a power of 150 uWatts. The laser comes equipped with a length of fiber attached to it. The light launched into this piece of fiber is split into two halves by the first coupler. One of these two halves is dissipated, the other half propagates into the second 2x2 coupler which then splits it into two other waves. The second coupler is connected to the 12 by 15 inch elliptical loop, where one kilometer of optic fiber is wound. One of the split waves travels in the clockwise direction, while the other in the counterclockwise direction. The two waves will recombine at the second coupler, and depending of the rotation of the system, will recombine constructively or destructively. The intensity of the light at this point can be described as:

I = [illegible] (1 - cos TH)

where TH = angle of rotation

The output intensity is its maximum when the TH is equal to zero

(Fig. 2.1) which is when angular velocity (Ω) of the Space Shuttle is zero. In the equation, "I" is independent of direction of rotation. Therefore, there is no way of differentiating between positive and negative rotation. Also when Ω = 0 the output corresponds to the least sensitive part of the rotational sensing curve.

To solve the above mentioned problems the light waves are submitted to a 90 degree phase bias. To do this a length of fiber is wrapped around the piezo electric cylinder, which expands and contracts at 80 kHz. Using this approach the positive and negative rotation rate of the Shuttle are discernible, and the most sensitive part of the curve is used. This way one wave will travel a distance of a quarter of a wavelength more than the other wave.

The PIN Fet photo detector receives and convert the light into a current. This current is integrated over a period of three seconds to average out the light level.

The system controller will keep the system on for three seconds out of every six. During the 3 second period, 2uSec pulses will energize the SLD and sense the rotation rate of the Shuttle every 125 uSec. Approximately 30,000 samples are taken over the 3 second period. The sum of these samples are held by a capacitor in the sample and hold circuit. The environmental data acquisition unit senses and records the voltage of this capacitor every six seconds. This process will be repeated at six second intervals, three seconds on -- three seconds off until the power cells finally become completely discharged.

As you can see in the system diagram (Fig. 3.1), we are using two couplers for the splitting of the waves. At first sight, this might seem wasteful because of three reasons. First of all, due to the two dead ends, we would lose half of the light intensity. Secondly, the addition of a second coupler would mean more weight, which is undesirable. Thirdly, the cost of each coupler is approximately $2,000. However, there is an extremely important reason behind this design. If one coupler is used, the lights that are to be compared would not have the same history; one would have been coupled twice, and the other transmitted twice (Fig. 3.3a). If, for example, the coupler introduces a polarization in the lights, the two would not combine properly. However, if we use two couplers, we can get two waves that are each coupled once and transmitted once (Fig. 3.3b). Now we can compare two waves with the same history (RT and TR). Experiments would be conducted to test the feasibility of using one coupler. The final decision on whether to use one coupler or two would be based upon tradeoffs, i.e. whether or not the above mentioned inaccuracies caused by using only one coupler are worth the savings.

MODIFICATIONS TO PROTOTYPE

The prototype, as can be seen on the system diagram on Fig. 3.1, makes use of two couplers. One modification that we propose is the use of only one coupler. This way the output of the loop will be taken from the free end of the coupler; this light energy was discarded in the previous design. The way we propose to test the feasibility of this design is to set the loop and diode up using only one coupler, and monitor the output current of the detector. If a good correspondence between the rotation of the prototype and this output voltage is detected, we will conclude that this arrangement is feasible.

Another modification that we propose is in the area of error cancellation. With the current method of measurement, any error in the phase bias will have a large effect on the output voltage. The relation is as follows:

$$Vout = A \cos (\underline{1 + } \sin (E+W))$$

where, Vout - Output Voltage

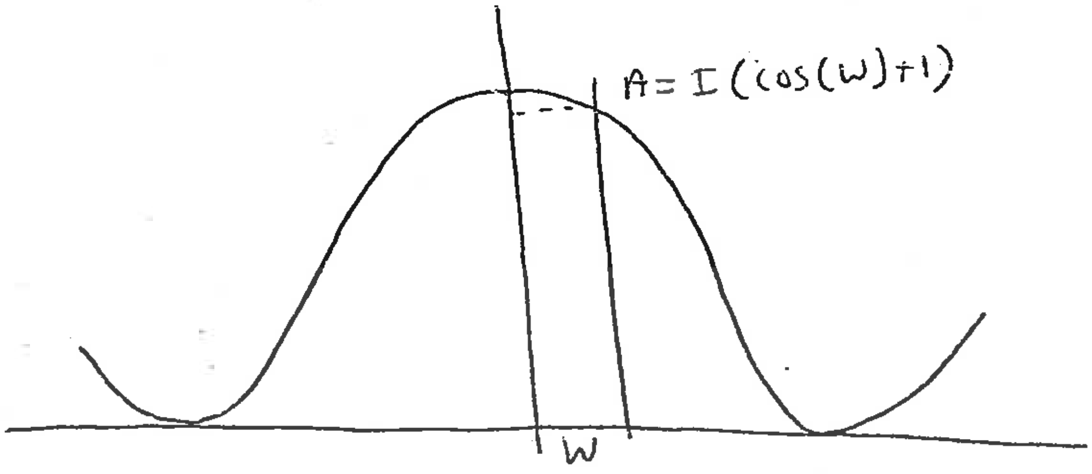
A - Proportionality constant

E - Error in Phase Bias

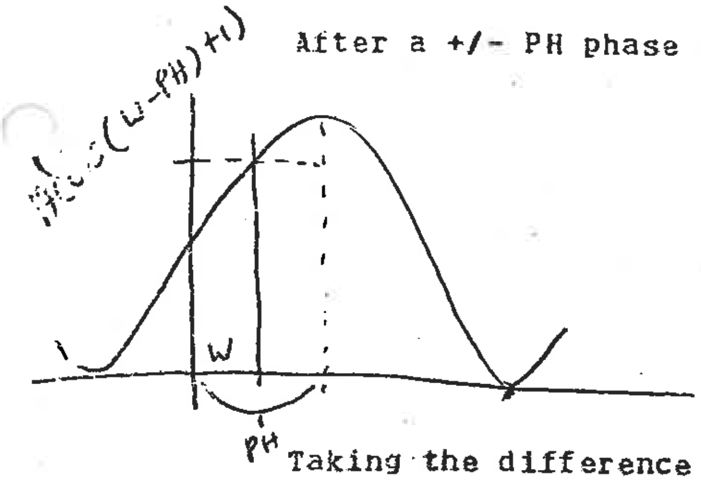
W - Angle between counter propagating waves due to rotation of shuttle

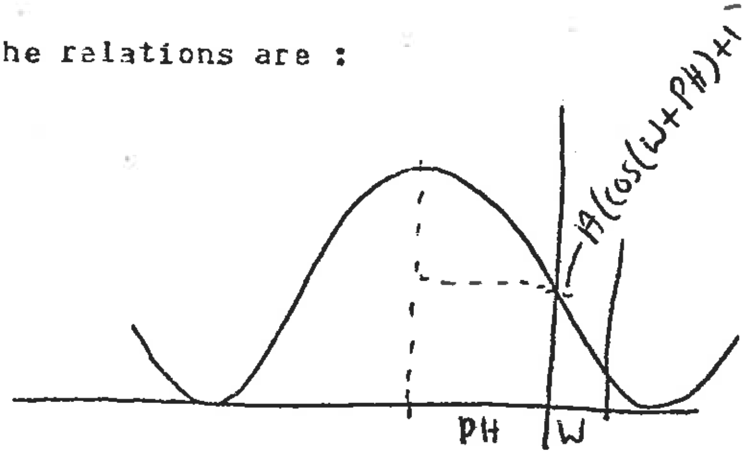
If the phase bias deviates from the calibrated mark of 90 degrees, it will distort the data. The modifications we have in mind is to introduce a phase bias that changes sign (but constant magnitude) every other cycle of the SLD. In other words, alternate the +90 degrees with a -90 degrees phase bias. The relation between the output and error is calculated below.

The relation between output and phase is as follows :

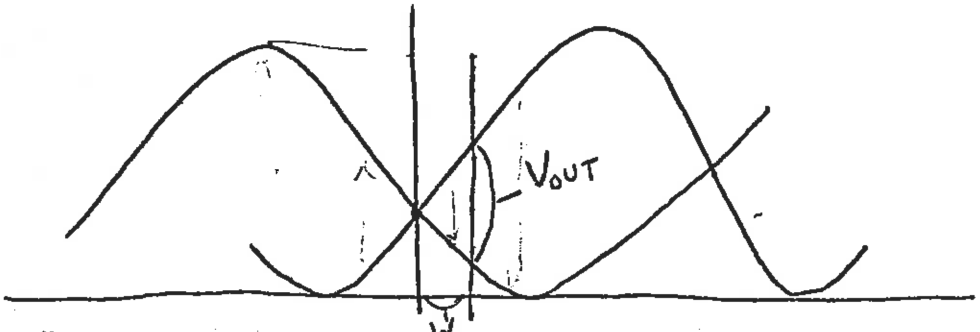


After a +/- PH phase shift the relations are :





Taking the difference between these curves :



$$
\begin{aligned}
\text{Vout} &= I\,(\,\cos(W-PH)+1\,) - I\,(\,\cos(W+PH)+1) \\
&= I\,(\,\cos(W-PH) - \cos(W+PH)\,) \\
&= 2I\,(\,\sin PH\,)(\,\sin W\,) \\
&= 2I\,(\,\sin(90+E)\,\sin W\,) \\
&= 2I\,(\,\cos E\,)(\,\sin W\,)
\end{aligned}
$$

Adding 2I bias so signal does not reverse sign

$$
\text{Vout} = 2I\,(\,(\cos E)(\,\sin W\,) + 1\,)
$$

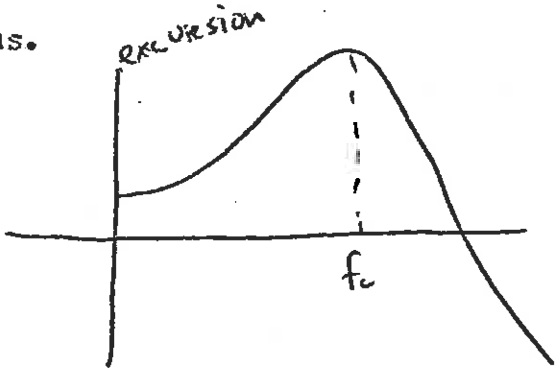
With the new switching bias the error, if close to zero, will have only a small effect on the output.

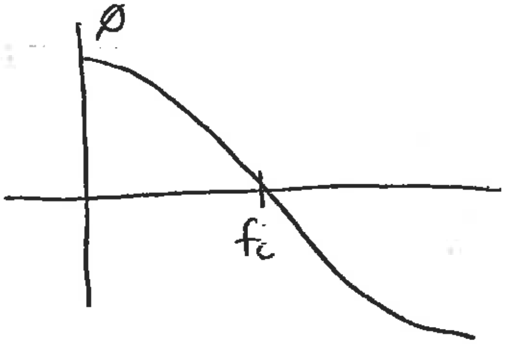
The hardware will not be very difficult to build for the above measuring scheme. The oscillator that drives the piezo cylinder is our master clock. It will run at approximately 80 kHz, and the rest of the circuit derives its timing from the cylinder. To introduce a positive phase shift on the piezo we trigger the SLD so that it fires on the rising slope of the sawtooth wave of the cylinder driver. In introducing a negative bias we simply have to trigger on the falling edge of the waveform.

At this point in the project, a system controller has already been built and tested. This controller has been wired together using wire-wrap however, and we will have to transfer it to a printed circuit board per instructions of Prof. Looit, leader of the technical steering committee. Depending on our decision of the error cancellation scheme we will also modify the operation of the controller itself.

A very important part of our system is the phase bias element. This device will be physically oscillating, and similar to all oscillating objects its excursion is temperature dependent. Any deviation from the calibrated point will introduce error in the output voltage of the integrator. Our goal is thus to monitor the status of the piezo ceramic cylinder, and to provide some form of feedback to control its oscillation. Up to now two methods have been thought up by the group. The first idea is to use a microphone pickup. The problem with this is the low sensitivity of current audio microphone to frequencies higher than 15kHz. This circuit is also sensitive to knocks and bangs caused by external noise sources, introducing noise in the feedback loop. Another idea is the use of a third electrode on the piezo cylinder. This third electrode can be fabricated by cutting and isolating a piece of the silver electrode on the cylinder. The signal tapped from this wire can be used as positive feedback to keep the oscillator going. In a sense the cylinder then becomes the crystal controlling the frequency of oscillation. This concept is used in many piezo buzzers incorporated in many alarm clocks.

Any deviation due to temperature will not only change the crystal's excursion due to the driving voltage, but will also introduce another serious source of error: a phase difference between the driving voltage and the resultant motion of the crystal. At resonance, the phase between the motion of the crystal and the driving voltage will be zero. Please see diagrams.





The SLD is triggered by the electrical signal, while the phase bias is related to crystal response. A deviation from resonance will cause the light waves to arrive at a different times at the cylinder than planned, resulting in a reduced phase bias.

The two last mentioned sources will add to increase the error caused by the temperature changes. The previously mentioned error canceling techniques will be tried if the crystal exhibits unacceptable temperature characteristics. We will investigate this by checking the crystal's response over a wide frequency range, comparing phase and excursion at temperatures from -20 C to +30 C.

The super-luminescent diode was to have a maximum power of 1mW. However, we were recently told that this has been reduced to 150uW. This is a reduction by a factor of 6.67. The output, which is collected by the data acquisition unit is a voltage whose maximum value is to be 5V. This is the result of the addition of 30,000 samples. So each sample should contribute up to (5V)/30,000)=.167 mV. This is the voltage on a capacitor which has a V-I relationship:

$$I = C\ dV/dt$$

Assuming a relatively constant current, which is the case for our square pulse:

$$I = CV/T$$

C and T are constants. So V is directly proportional to I, which is in turn directly proportional to the light impinged on the detector. So if the light intensity drops by a factor of 6.67, I and V would drop, and the amplification would have to be boosted up by the same factor. This would in turn cause more noise, which would decrease the SNR.

IMPLEMENTATION

Since the axis of the loop has to be parallel to the roll axis of the shuttle, the plane on which it is to be implemented would have to be placed parallel to the cannister walls. The plane itself is a square. However, since the side of the cannister is curved, the loop, which has a certain width, would not fit if it were to use the entire plane. See diagram:

Thus, fitting a perfect circle on it would mean a reduction in the area: The maximum possible radius would approximately be .165m. Consequently, the maximum area would be:

$$A_1 = 2\pi r_1 = .0855m$$

But fortunately, the Sagnac effect is independent of the shape of the loop. However, it does depend on the area enclosed by it:

$$\Phi = 8\pi\omega(NA/c\lambda)$$

To take advantage of maximum space allotted, the loop was chosen to be elliptical, with radii of .184m and .165m. This would yield a surface of:

$$A_2 = \pi r_2 r_3 = \pi(.184m)(.165m) = .0953m^2$$

This represents a gain in area of:

$$\left(\frac{A_2 - A_1}{A_1}\right)(100) = \%11.5$$

As you can see, the phase shift, Ø, also depends on the number on turns, N. Using an ellipse would decrease the number of turns. With a circle, we would have a perimeter of $P_1 = 2\pi r_1$, and the number of turns would be:

$$N_1 = \frac{1km}{2\pi r_1} = 964.6 \text{ turns}$$

The perimeter of an ellipse is approximately equal to:

$$P_2 = 2\pi\sqrt{\frac{r_2^2 + r_3^2}{2}} = 1.098m$$

and consequently, we would have:

$$N_2 = \frac{1\,Km}{1.08\,m}$$ = [illegible].7 turns

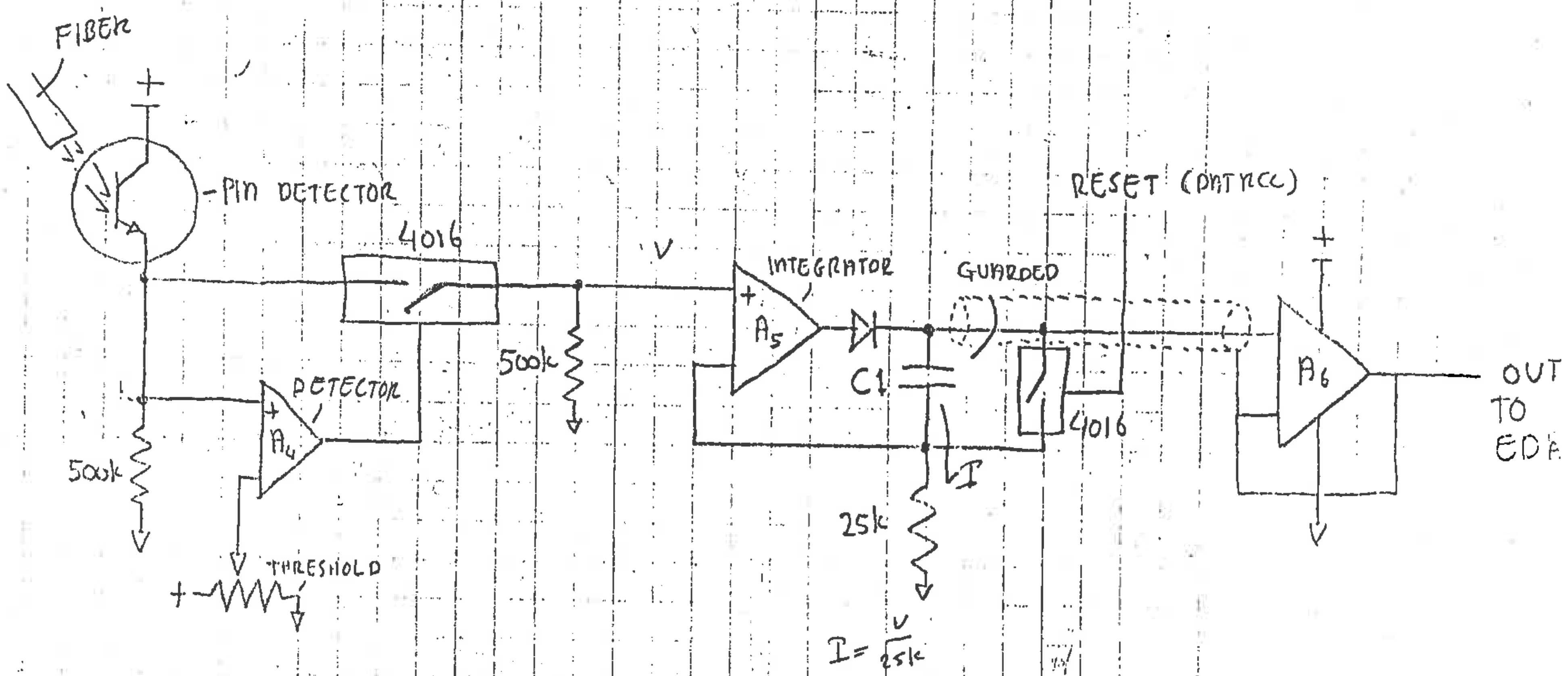
Now the percent increase in accuracy would be:

$$\frac{N_2 A_2 - N_1 A_1}{N_1 A_1} = \%\,5.2$$

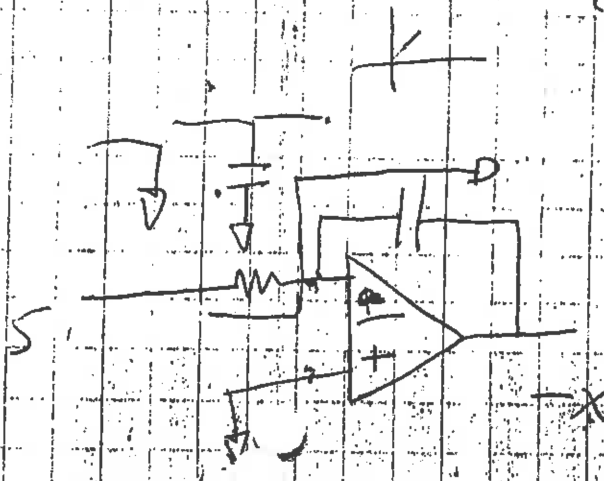
There is one more advantage to this design: Since the number of turns is reduced, the width of the loop would also be reduced, and we would be able to use a little more of the mounting plane. The elliptical loop is currently being built by the mechanical assembly team and is made of fiber glass. The electronic devices would go inside the loop. Please see diagram.

Preliminary circuit diagram for the Integrator and the Piezo Driver are on figures A and B. The designs are the product of the Rookie group, and are only preliminary because decisions concerning error-canceling techniques have not been finalized. What has been designed is for the simplest option: constant phase bias, pulsed SLD operation. A brief circuit description follows. Our high voltage source will be a coil pulsed by a 7555, micropower version of the 555 timer. This simple DC-to-DC converter provides approximately 50 or more volts. The converter needs only to supply about 1 mA, since the piezo is a very high impedance device. This voltage is effectively regulated because it is inside the feedback loop of op-amp A1, together with Q1. Due to feedback any voltage applied to A1 is amplified and applied to PZT. A2 and A3 are signal-conditioning circuits to pick off the waveform applied to PZT, and the two flip flops issue a very accurate 2uSec pulse to the LED. The width of this pulse is critical because the output pulse is the result of an integration. Any deviation in length of the pulse will result in erroneous output. A4 will turn on the integration if the input light level is higher than a preset amount. This will reject any backscattered light to increase the signal to noise ratio. A5 is the voltage-to-current converter that charges the capacitor, and finally A6 is a buffer echoing the voltage on C1.

INTEGRATOR



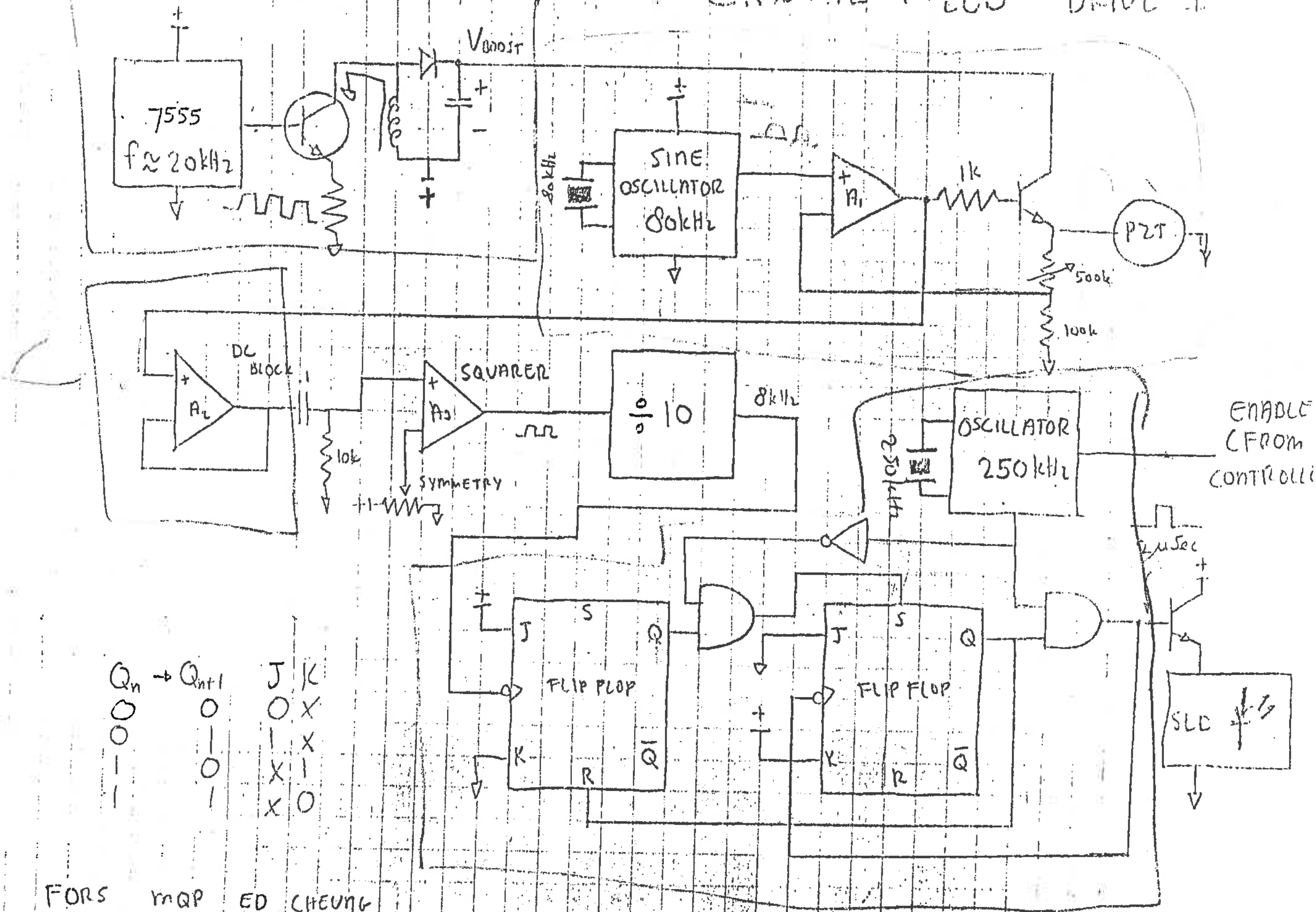
Op-Amps : 357
SLEW 50 V/us
BW 15 MHz
JFET INPUT
OR EQUIVALENT



4016 QUAD CMOS BILATERAL SWITCH

FORS MQP ED CHEUNG

CRYSTAL + LED DRIVE



$Q_n \to Q_{n+1}$	J	K
0 0	0	X
0 1	1	X
1 0	X	1
1 1	X	0

FORS map ED CHEUNG

ANTICIPATED PROBLEMS

Since we are measuring the phase difference between two waves, any optical noise that is reciprocal, i.e. effecting both components equally, as long as it is small compared with the power in the light beam, would only decrease the sensitivity of the signal, in the sense that the detection would be more difficult (might require better timing, filtering ...etc). On the other hand, nonreciprocal noise, which affects the two waves differently, could cause much greater errors, because it can result in erronous drifts in phase, which could be mistakenly taken for rotation. Possible sources of optical noise are polarization and Faraday effect. Also, any nonideal electrical system has a certain amount of noise associated with it. Ours is not an exception. Other possible factors are shot noise and modemixing.

When nonpolarized light is split by a beamsplitter, the reflected fraction is partly polarized parallel to the beamsplitter surface, and the refracted part tends to have a polarization perpendicular to the surface (see fig. C). The partial polarization becomes %100 polarization when the reflected wave is at right angles with the refracted one. When this situation occurs, the angle of incidence, θ, is called Brester's angle. As long as our couplers don't use plane surfaces to split the beams, this situation would not occur. But similar problems with polarization might occur, none of which could be predicted before experiments are conducted with the polarization.

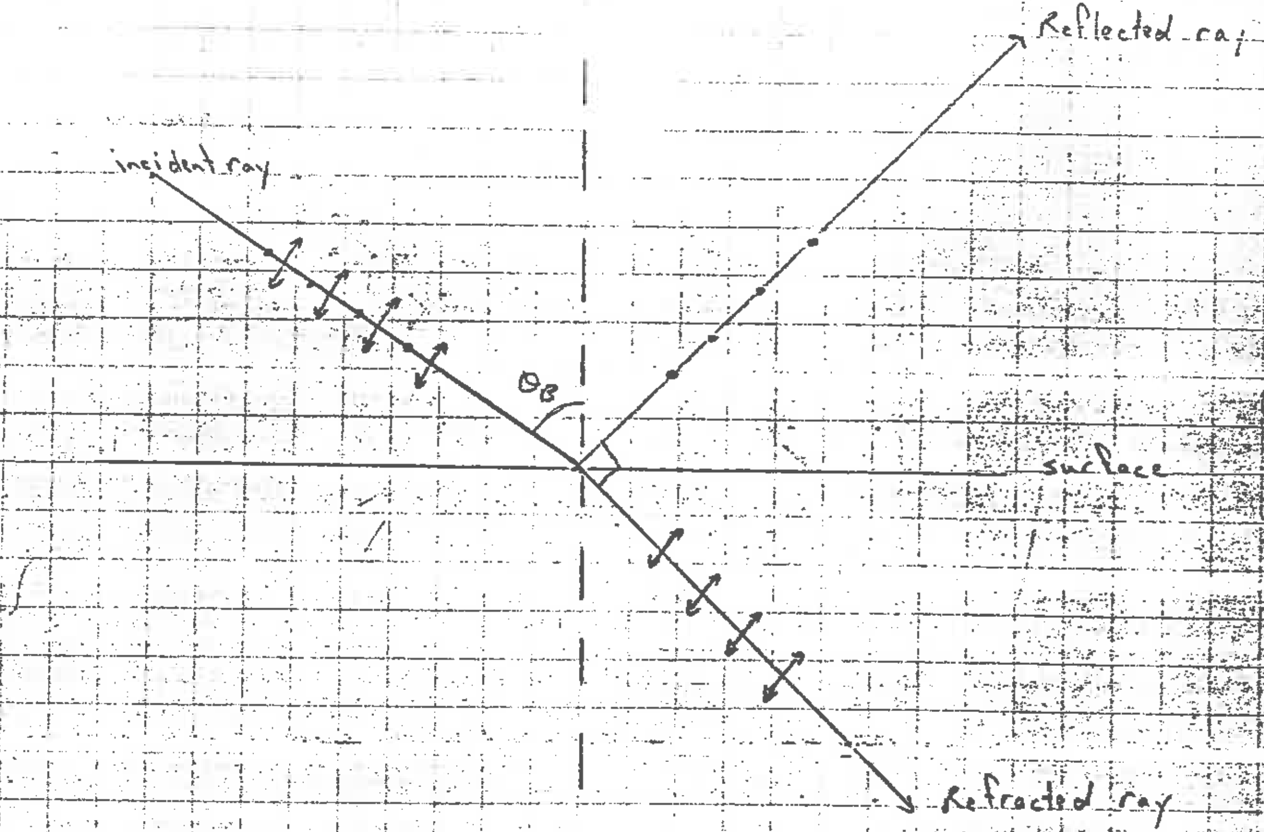


Figure C - Polarization by Reflection

Depending on the noise caused in the system due to polarization, we might have to use one or more polarizers to place at different stages of the process, and use polarized light throughout the process.

Another source of noise associated with the polarization is the Faraday effect. Light, when passing through a magnetic field, changes polarization. Our concern is with the effects of earth's magnetic field on the beam. If our light remains unpolarized throughout the system, a shift in polarization would not affect anything. On the other hand, if partial polarization occurs, or if polarizers are used, this noise source could become significant. Obviously, the only way to find out about this is by experimenting.

Shot noise is a "ripple" that might occur in the output reading, as individual photons hit the detector. The energy associated with each photon is:

$$E=hv$$

where v is the frequency of the photon and h is Plank's constant, 6.625×10^{-34}. In our case, the frequency of propagation is approximately equal to:

$$v \approx \frac{2\times10^{8}\ m/sec}{1.3\times10^{-6}\ m} = 1.54\times10^{14}\ Hz$$

So the energy associated with every photon of light would be:

$$E=(1.54 \times 10^{14}\ Hz)(6.625 \times 10^{-34}\ J\text{-}sec)= 10^{-19}\ J$$

a total loss of approximately 9.46dB is anticipated. Therefore, the power in the light reaching the detector, after going through the attenuations, is about %10 of the input, in the order of fifteen microwatts. The duration of every pulse is 2usec. Therefore, the energy in every pulse is in the order of:

$$E \approx (15 \times 10^{-6} W)(2 \times 10^{-6} sec) = 3 \times 10^{-11} J$$

Now we can calculate P, the number of photons in every pulse:

$$P = \frac{3 \times 10^{-11} J}{10^{-19} J} = 3 \times 10^{5} \text{ photons}$$

The detector turns light (photon flow) into current (electron flow). The number of electrons flowing is directly proportional to the number of photons reaching the detector. Denoting the current by I, the number of electrons flowing would be:

$$n = I/e$$

where $e = 1.6 \times 10^{-19}$ C is the charge of an electron. The period of the pulse is 2usec:

$$T = 1/2B = 2usec$$

So the total number of electrons in every measurement would be:

$$N = nT = (I/e)(1/2B)$$

Denoting the error in the number of electrons by N, we have:

$$\Delta N = \sqrt{N}$$

The above equation holds for our system, because each electron arrives at the capacitor independent of the others. So:

$$\Delta N = \Delta I/2eB$$

And the error in the current is:

$$\Delta I = e\Delta N/(1/2B) = 2eB\Delta N$$

Assuming a quantum efficiency as low as %1 (every 100 photons of light cause one electron of current), we would have a total number of electrons equal to:

$$N = (3 \times 10^{8})(.01) = 3 \times 10^{6}$$

and the error in the above would be: $\Delta N = \sqrt{N} = 1.73 \times 10^{3}$ and since $I = 2eBN$, we have $\Delta I = 2eB\Delta N$ Now the percent error could be calculated:

$$(\Delta I/I)(\%100) = [(2eB\Delta N)/(2eBN)](\%100) = \%0.0577$$

Obviously, this is not a significant noise level. Therefore, shot noise should not be of significant importance.

When light, consisting of components in certain modes is transmitted through an ideal fiber, it retains its shape, and reaches its "destination" without any part of it going to a diferent mode. But any nonideal optical fiber has imputities, air bubbles, slight bendings, and other material problems, which cause light to go from one mode to another. This is called modemeixing. Since our fiber is single mode, these light components would not propagate inside it, and would immediately scatter into the environment. So this should not be a source of noise at the detector, but rather a cause for losses during propagation.

TESTING PROCEDURE

We have been able to obtain only very little information about our piezo cylinders from its manufacturer, Vernitron. Up to this point we can only estimate the number of turns of glass fiber that we will have to wrap around the cylinder to produce the correct amount of phase bias. We also have very little idea of our cylinder's temperature stability. This forces us to determine these parameters experimentally, an advantage because it will enable us to gain experience in the use of these devices. Over the summer several of our team members, in particular Edward Cheung, intend to do some experimentation with the five cylinders that we have in our possession.

To test the rotational sensor we will need a turntable that spins very slowly and accurately in the range of .001 to .01 rpm. There is a turntable at WPI, but this table spins far too fast. We will probably have to modify a record turntable for our purposes. There might also be one at Mitre or MIT which we could borrow to test our sensor.

The system would be expected to endure a vibrational force of 12g. Since the canister is being shared by several projects, it is crucial that nothing comes loose during take-off. Since the optical loop and the electronic components are attached only by cables, the vibration testing would be conducted on the loop and the electronics section separately. This would be done by mounting the components onto a shake table exactly as they would be set up in the canister. Each component would be tested three times, each time the vibration being applied at a different axis. The frequency range would be from 20Hz to 2KHz.

There would also be an acoustical testing. An acoustical vibration of 145dB, ranging in frequency from 10Hz to 5KHz, would be applied to the different components, to see if they can endure the acoustical vibrations.

Since the sensitivity of the system is directly affected by the power in the light impinging upon the detector, every effort would be made to minimize the loss during propagation through the fiber and the couplers. One important cause of the loss of power is bad matching between the cores of different pieces of fiber, at connection points. When connecting fibers from the different components, accurate alignment is difficult, because the fiber core has a radius of only 7um. At MITRE, there is a device, which when connected to the end of a fiber, would show how much power is flowing through it. During splicing, by having one end of the fivers connected to a light source and the other end to this apparatus, we can align for minimum loss. Obviously, there would always be losses at the connection points, but these would hopefully be controlled so as not to affect the overall efficiency.

The major sources of loss in the system are the couplers and the fiber loop itself. In the forward path, the first coupler sends half of the wave into a dead end, causing a loss of 3dB. On the path to the detector, the second coupler sends 3dB of the wave into the dead end, and the first coupler sends another 3dB back into the SLD. This adds up to a total of 9dB. The fiber itself has a loss of 0.46db/km. This would give a loss of approximately 0.46dB in the loop. So the total loss is 9.46dB Consequently, 11.32 of the power would reach the detector. These are losses that even a system with perfect splicing, detection ...etc would suffer. The 9dB loss mentioned above is the main reason why we are looking into the use of one coupler.

Since the canister would have to be sent down to NASA several weeks before the actual flight, precautions must be taken to make certain that everything is working at launch time. The prototype would be set up and left idle for a long period, and then turned on. At this time, two things would have to be checked:

1) The system would be tested for any drift in phase as a result of the long time-lapse.

2) The batteries would be tested to see how long they will supply enough power for the system to function properly. When analyzing the data after the flight, the team would know how much of it is accurate. Based on a power consumption of 6mA (p56 of vet's report) we anticipate that the project will run for about three days.

APPENDIX A - System Mechanics

For information on Weight, Size, and Volume please see page 56 of veterans' report.

A diagram of the system placement in the canister is on page 9 of this appendum.

APPENDIX B - Development Schedule

1) SUMMER '84 - Acquire Parts

   - Investigate Properties of Piezo

   - Research in Fiber Optic Field

2) A-TERM '84 - Design and Breadboarding of Circuits

   - Construction of Fiber Loop

   - Construction of Phase Bias Element

   - PC-board Artwork

3) B-TERM '84 - Populating PC-boards

   - Preliminary Testing

   - Construction and Hookup

   - Report to Technical Steering Committee due Dec. 31

4) C-TERM '85 - Testing and Improvement

   - Shake Test

5) D-TERM '85 - Making System Space Ready

- Calibration

- Long Term Drift Test

- Final Report

n) Summer '85 - Installation into GASCan

APPENDIX C - Parts not Currently Available

All parts except the 50-50 couplers have been either donated or bought. We will try over the summer to get these couplers donated. However, if we do not succeed we will have to buy these couplers. The couplers' specs are : single mode, stepped index, 50-50 (or 3dB), and operating at a wavelength of 1.3 microns.

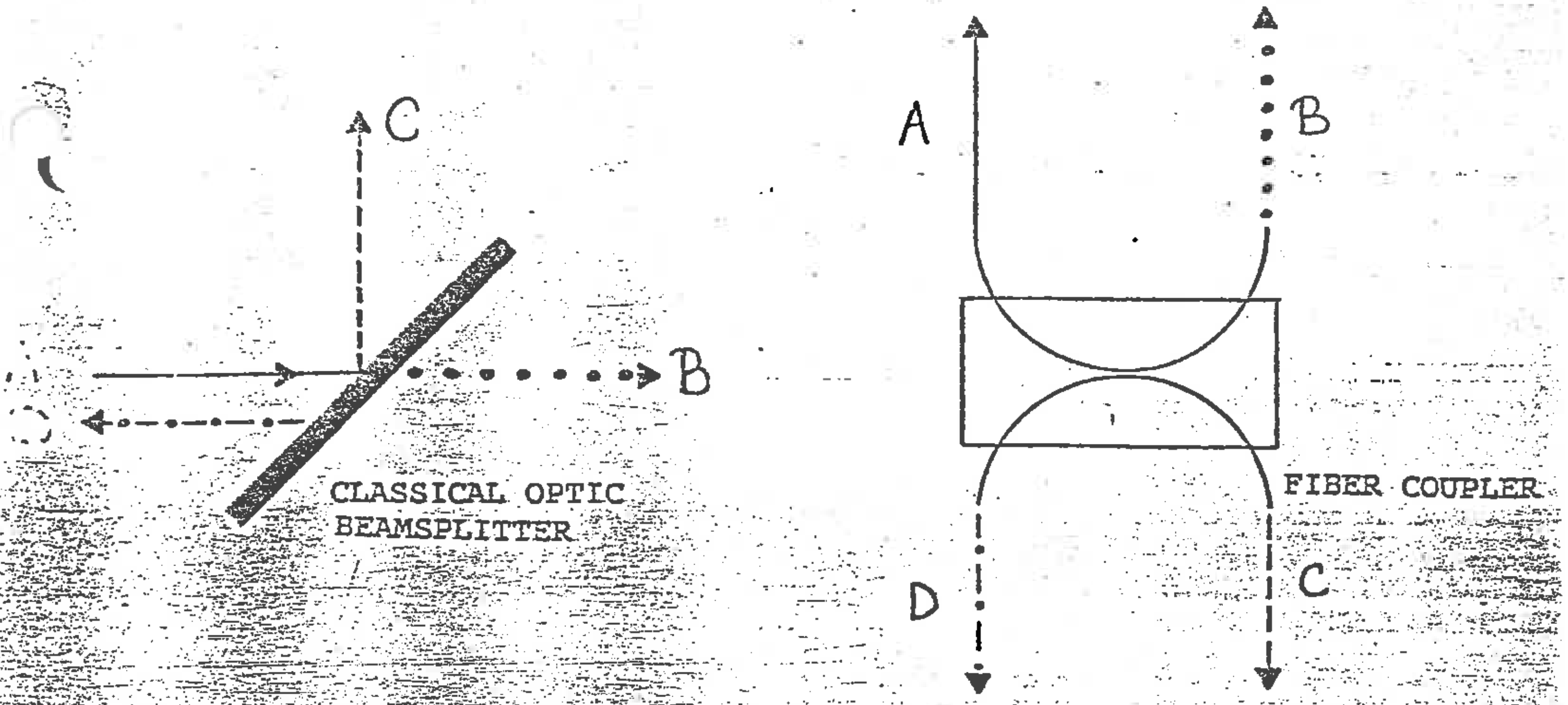


Figure 3.2
Equivalency of a Fiber Coupler and a Beamsplitter

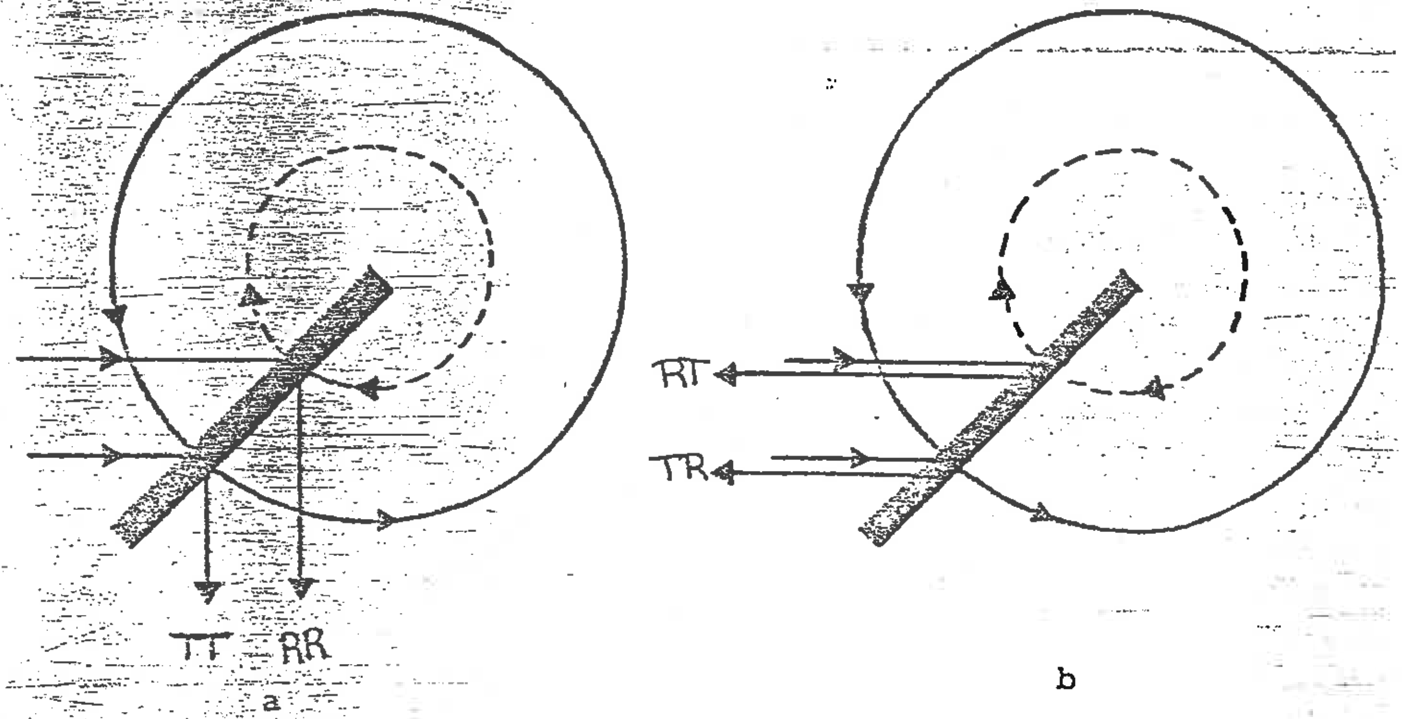


Figure 3.3
Possible Light Paths Through a Beamsplitter

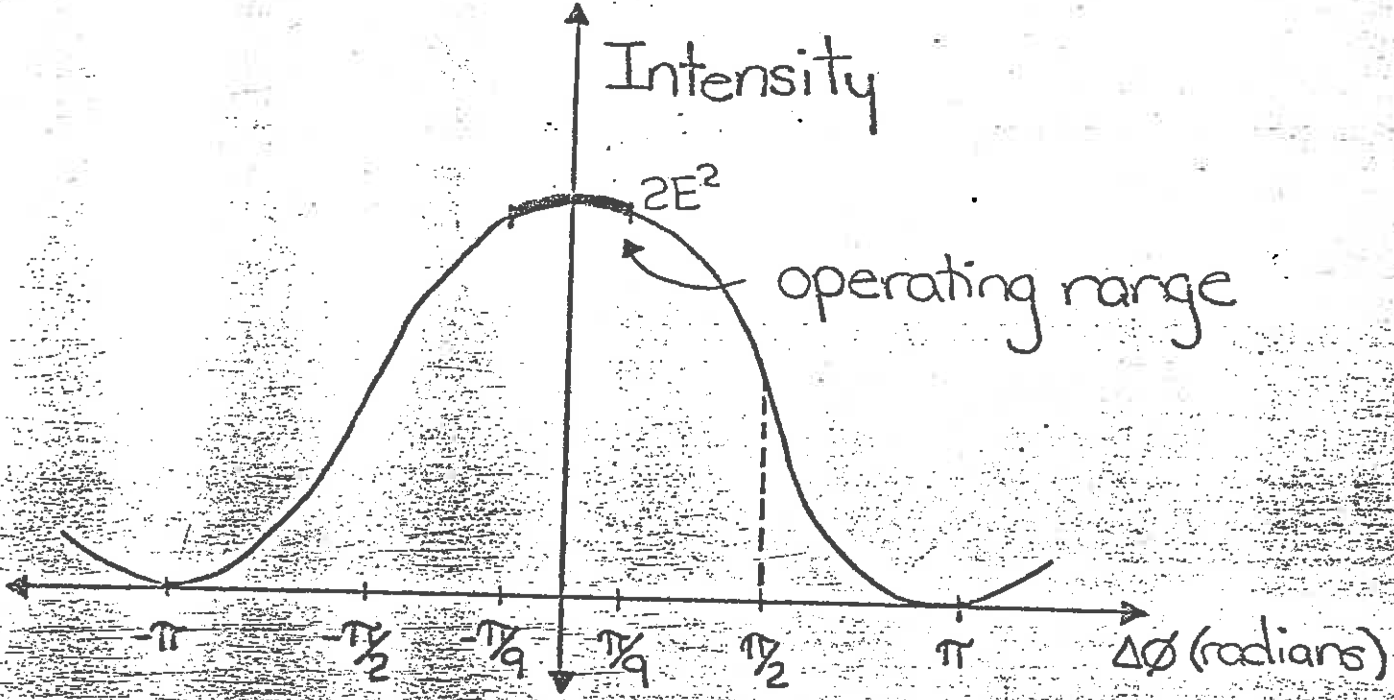


Figure 2.4a
Output Intensity Curve

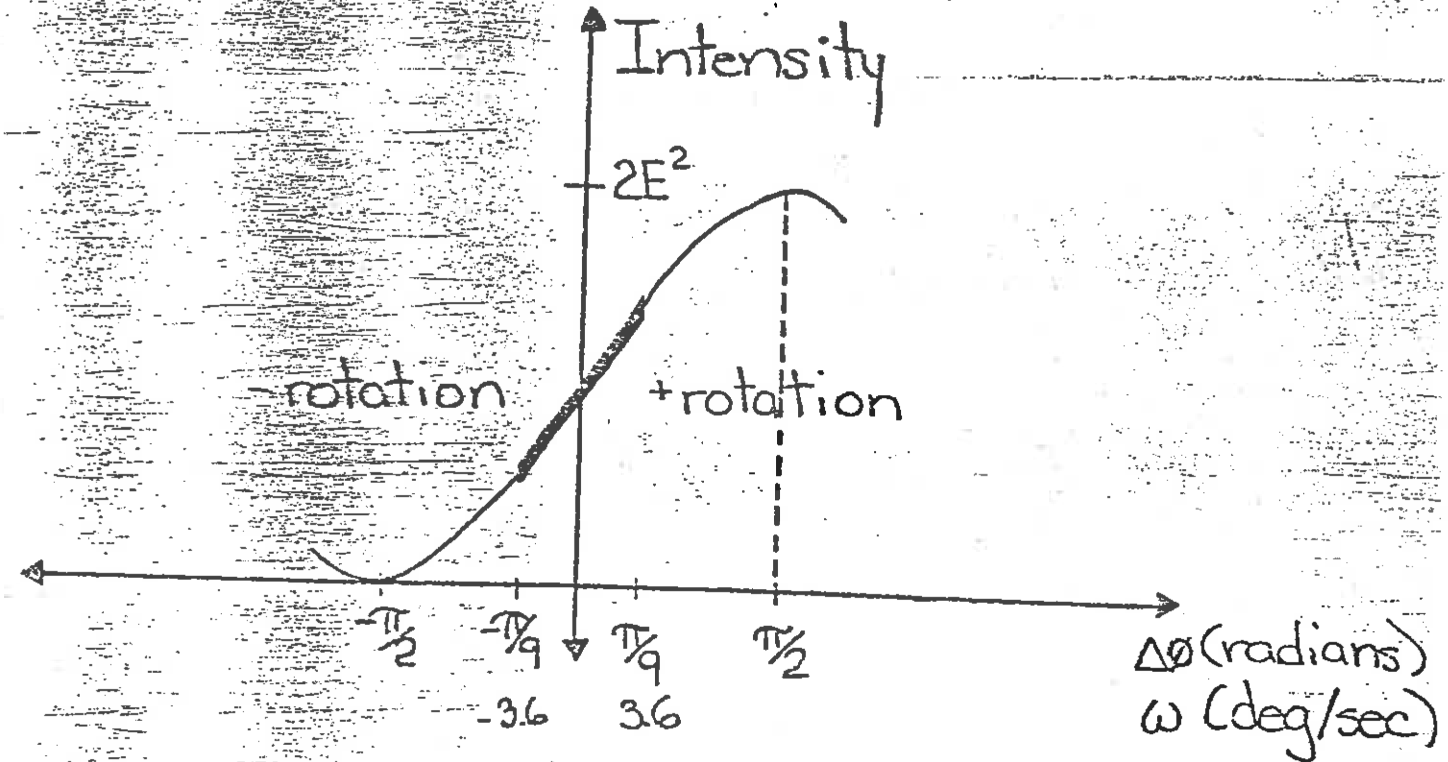


Figure 2.4b
Output Intensity Curve with a 90 Degree Phase Bias

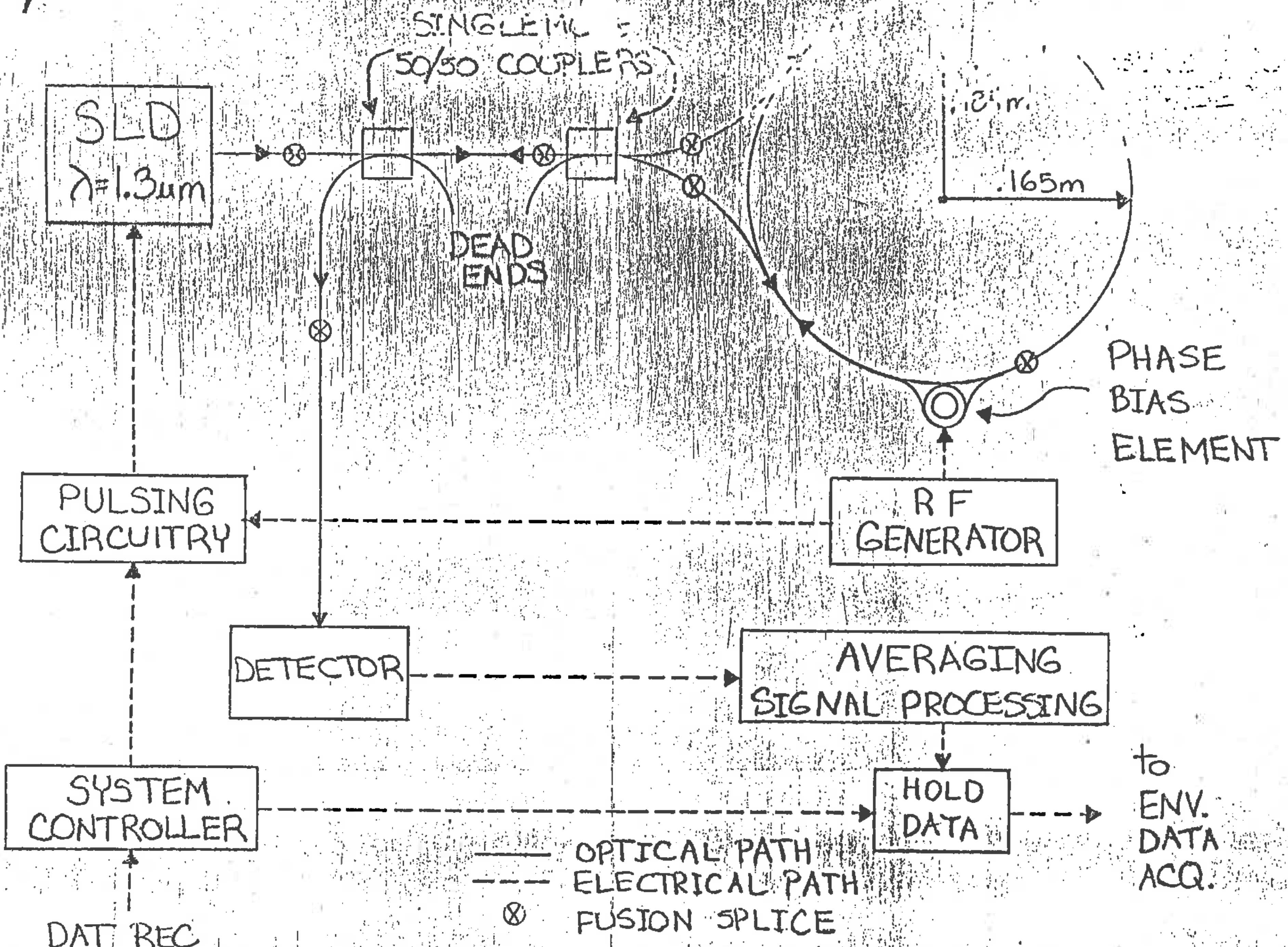


Figure 3.1
Rotation Sensor Functional Block Diagram