A Solid State Transducer for Monitoring Pipeline Cathodic Protection Voltages

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A SOLID STATE TRANSDUCER FOR MONITORING PIPELINE CATHODIC PROTECTION VOLTAGES

BY

JON ROBERT BARTELL
B. S. E., Florida Technological University, 1973

THESIS

Submitted in partial fulfillment of the requirements for the degree of Master of Science in Engineering in the Graduate Studies Program of Florida Technological University

Orlando, Florida
1974
ACKNOWLEDGMENT

The author wishes to thank the Electrical Engineering Department of Florida Technological University for its assistance in making this thesis possible. In particular, the author would like to express his sincere gratitude to Professor Ed R. M\u00e2Carter for his guidance and expertise throughout the research and writing involved in this endeavor. Only with the help of Dr. M\u00e2Carter was the author able to complete this paper. Finally, the author wishes to express his special thanks to his wife, Loretta, for typing this thesis, and for her patience and encouragement during the writing.
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Introduction

At this time there exists a need for a better method of monitoring the cathodic protection voltages on underground gas pipelines. At present Florida Gas Company has approximately 4,000 miles of buried pipeline carrying natural gas from Texas to Florida. In order to prevent corrosion of the metal pipe, a cathodic protection voltage is applied between the pipe and earth ground which opposes the natural voltage that develops through chemical action. The voltage that is applied to the pipe is obtained from the power lines by use of a step-down transformer and rectifiers. These voltage generating sites are located approximately five miles apart along the pipeline where possible. Florida Gas Company desires the voltage from the pipeline to ground to be between -0.85 V and -2.0 V. In order to measure this voltage, measurement sites are located approximately one mile apart along the pipe. The measurements of these voltages are currently being obtained by personnel on foot using voltmeters. Due to the large number of measurement sites and the fact that some of these sites are inaccessible, it is desirable to find a faster and more economical method of monitoring these sites.

Florida Gas Company has an aircraft which periodically flies along the pipeline to inspect for leakage and other problems, and desires the capability of measuring the cathodic protection voltages with this aircraft. This makes it necessary to transmit a signal representing the
pipeline voltage to the aircraft. In order to transmit the pipeline voltage data to the aircraft, it was decided to use a laser transmitter rather than an RF transmitter since it was felt that the laser would be more immune to atmospheric disturbances and there would be no licensing involvement with the F.C.C. The original concept involved deriving the operating voltages for the transmitter from the pipeline cathodic protection voltage. Florida Gas Company believed that 10 milliamperes of current could be drawn from the pipeline without adversely affecting the pipeline protection. Subsequent field tests conducted in the Orlando area showed that the impedance from the pipe local ground to earth ground was considerably higher than expected. It was felt that an impedance on the order of 25 ohms or less was acceptable. During the field tests copper rods were driven into the ground near the pipe in an attempt to achieve this impedance. In some high lying areas many rods would be needed to achieve a 25 ohm impedance, which would increase the cost of the transducer installation, in addition to which it would be necessary to send crews to each site to implant the copper rods. It was felt that a more economical method of circuit power should be used. To this end, battery power with a solar cell charger was considered. This proved to be more economical and makes installation a "bolt-on" process.

The transducer circuit designed to meet the objectives of above can be divided into three sections: the power supply, the voltage to pulse rate converter, and the laser transmitter.

The power supply utilizes the battery-solar cell power source to
produce power for the entire transducer. An inverter is used to convert
the 1.25 V DC from the battery to AC which is then stepped up and recti-
fied for use in the power supply voltage regulators. Two regulated
voltages are required in the system: 60 V to power the laser diode, and
5 V to power the voltage to pulse repetition rate converter. Also, part
of the power supply is a circuit which turns the transducer off at night
to conserve the battery energy.

The voltage to pulse repetition rate converter monitors the pipe-
line to ground voltage and uses this voltage to control the frequency
of a pulse generator, thus making the pulse rate a function of the volt-
age. This section also contains compensating components to reduce pulse
rate variations with temperature changes. The pulses out of this sec-
tion are used to drive the laser transmitter.

The laser transmitter consists of a GaAs semiconductor laser and
its firing circuit. The firing circuit utilizes the regulated 60 V sup-
ply to fire the laser at the rate determined by the voltage to pulse
repetition rate section.

When mounted, the laser is orientated such that the beam is direc-
ted vertically upward. The aircraft flying over a test site can use a
receiver with an optical detector to detect the pulse rate and thus the
cathodic protection voltage. Although the receiver design is not with-
in the scope of this project, a laser detector and preamplifier were
designed and built to allow monitoring of the laser diode's optical
output.
Theoretical Considerations

A. Ground Impedance

As explained in the introduction, the original desire of Florida Gas Company was that the transducer be powered from the voltage on the pipe. Considering a power source of 0.6 V for the transducer and a current of 10 milliamperes drawn, implies that the transducer would place a 60 ohm load in series with the pipeline-to-ground circuit. In order to prevent the transducer load from affecting the pipeline to ground voltage, it is necessary that the ground impedance, i.e., the impedance from the pipe's local ground to earth ground, be considerably lower than 60 ohms. It was decided that a ground impedance of 25 ohms would be an acceptable value. Figure 1 shows the results of field tests conducted at six test sites near Orlando.

The ground impedance was measured as follows. Copper rods were driven into the ground and the voltage from the copper rods to the pipe was measured with a bridge type voltmeter. A decade resistance box was then connected from the pipe to rod and adjusted until the voltage dropped to half of the value found above. This value of resistance is then equal to the ground resistance.

From Figure 1 it can be seen that the ground impedance varies from site to site. It can also be seen that the protection voltage varies
<table>
<thead>
<tr>
<th>SITE</th>
<th>PIPE TO GROUND VOLTAGE (VOLTS)</th>
<th>ROD TO EARTH GROUND IMPEDANCE (OHMS)</th>
<th>NUMBER OF 4 FOOT RODS</th>
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<tr>
<td>1</td>
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<td>--</td>
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<td>.47</td>
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Figure 1 Results of Pipeline Ground Impedance Field Tests in Orlando Area
from site to site. This would place additional constraint on the power supply circuit design. It was decided, therefore, that a solar cell-battery power supply would be more economical, as well as resulting in a more simple power supply circuit configuration.

B. Solar Cell and Battery Power Supply

The decision was made to operate the transducer circuit from a battery and solar cell combination with the solar cells furnishing power when there is sufficient sunlight and the batteries providing power during cloudy or rainy days. It was decided to turn the transducer off during the night to conserve the battery energy. It was also decided to stay with the original power drain requirements, that is, 10 milliamperes at approximately 0.85 V to 1.5 V. A rechargeable nickel-cadmium size "D" battery rated at 1.25 V with 4 AH capacity was chosen for this purpose. This battery will provide power for the transducer for approximately thirty days without sunlight at a current drain of 10 milliamperes. The silicon solar cells chosen produce 0.4 Volts per cell in bright sunlight at a current of 60 milliamperes. Placing five of these in series will provide the needed voltage and have five times the current capacity needed to operate the circuit. Therefore, it was concluded that if there is sunshine 1/5 of the daylight hours it will be possible to power the circuit and keep the battery charged. Figure 2 shows a plot of solar cell voltage versus current for five silicon solar cells in series. This plot was obtained in bright sunlight, by connecting a decade resistance box across the solar cells and measuring the voltage output as the resistance was varied.
Figure 2 Voltage Versus Current For Five Silicon Solar Cells in Series
C. Laser Power Considerations

The laser chosen for the optical transmitter portion of the transducer is an LD 63 Gallium-Arsenide semiconductor laser diode. This unit has a peak optical power output of 5 Watts, with corresponding input current of 25 Amperes and voltage of approximately 12 Volts. Figure 3 shows a plot of the laser current as a function of laser voltage. Since for a 5 Watt output the input power is $25 \text{ A} \times 12 \text{ V} = 300 \text{ Watts}$, the efficiency of these semiconductor lasers is quite low. The maximum recommended pulse duration for this laser is 200 nanoseconds. This corresponds to a maximum energy input per pulse of $12 \text{ V} \times 25 \text{ A} \times 200 \text{ nsec} = 60 \text{ micro Joules per pulse}$. The laser is fired by charging a capacitor during the laser offtime and then discharging the capacitor through the laser by turning on an SCR. The value of the capacitor is calculated as follows. Assume the capacitor discharges exponentially through the series resistance of the SCR and laser diode and that a pulse period of 200 nanoseconds is desired. Assuming the capacitor essentially discharges in 5 time constants the time constant is then

$$t = \frac{200 \text{ nsec}}{5} = 40 \text{ nsec}.$$

From the plot of laser current versus voltage, it can be seen that the laser impedance is approximately equal to 0.4 ohms. The SCR on resistance was found to be 3 ohms. The total series resistance is then 3.4 ohms. Therefore, the equation

$$t = RC$$

or

$$40 \text{ nsec} = 3.4 \text{ C}$$
Figure 3  Laser Diode Current as a Function of Laser Diode Voltage
implies
\[ C = 0.017 \text{ uF}, \]
so that a 0.02 uF capacitor was chosen. Now the energy per pulse considerations require that the capacitor charge to 77 V, i.e.:
\[ E = \frac{1}{2} CV^2 \]
\[ 60 \text{ uJ} = \frac{1}{2} \times 0.02 \text{ uF} \times V^2 \]
\[ V = 77 \text{ V} \]
Since this calculation is for the maximum laser energy input, the supply voltage was chosen to be 60 V. As can be seen from the plot of laser current versus time in Figure 4, the capacitor discharge is not strictly exponential. This is due to the influence of the inductive reactance associated with the interconnecting wiring.

D. Pulse Rate as a Function of Beam Width, Aircraft Velocity, and Aircraft Altitude

As the aircraft flies over the test site it is necessary that enough pulses are received at the aircraft to determine the pulse repetition rate. The laser pulse repetition rate is a function of the laser beam width, the aircraft velocity, and the aircraft attitude. It was learned from Florida Gas Company officials that the aircraft normally flies at an altitude of approximately 100 feet at a speed of 100 MPH. The laser beam spread is specified to be 15 degrees. Now, in order to measure the period of the pulse repetition rate, at least two pulses must occur while the aircraft is within the laser beam. However, it would be desirable to receive more than two pulses as a check. Using 100 MPH as the aircraft velocity, 15 degree laser beam spread, and
Figure 4  Current Pulse for LD63 Laser Diode
assuming the aircraft flies at 100 foot altitude through the center of the beam, then calculations show that the aircraft will be in the beam for 183 milliseconds; thus making the maximum pulse period 20 milliseconds will give at least 9 pulses while the aircraft is over the laser. Of course, any faster periods will give more pulses; however, faster pulse rates increase the power supply drain. The range of pulse periods was chosen to be 20 milliseconds to 10 milliseconds corresponding to an input voltage of 0.85 V to 1.5 V and resulting in a 2 to 1 frequency change over the desired voltage range. Figure 5 shows the pulse period $t$ as a function of input voltage $V_x$.

E. Pulse Rate Converter Period Calculations

This section shows the calculation of the period of oscillation for the voltage to pulse repetition rate converter shown in Figure 6. As stated in the previous section, the desired pulse period is 10 milliseconds to 20 milliseconds. The oscillator used for this circuit is a complementary multivibrator. The detailed operation of this circuit is explained in the section on experimental results. For the calculations of this section, it is sufficient to realize that $C_1$, a 0.0015 uF capacitor, must charge from -4.4 V to +0.6 V, a change of 5 V. The current to charge this capacitor comes from constant current source $Q_1$. The collector current of $Q_1$ is proportional to the pipeline voltage being monitored.

Assume the voltage at the base of transistor $Q_1$ is 3.4 V, then the emitter voltage is approximately 4 V, and the emitter current, which is
Figure 5  Laser Pulse Period (T) as a Function of Cathodic Protection Voltage ($V_x$)
approximately equal to the collector current, is

\[ I = \frac{1}{2.2 \text{ Megohms}} \frac{V}{2} = 0.45 \text{ uA} \]

\[ V(t) = I \times C \times \frac{1}{C} \times t + V_0 \]

Since the capacitor is being charged by a constant current, \( i(t) \) can be taken outside the integral and

\[ V_c(t) = I \times t + V_0 \]

then

\[ V_c - V_0 = I \times t \]

solving for \( t \)

\[ t = \frac{C}{I} (V_c - V_0) \]

where \( V_c = 0.6 \text{ V} \), \( V_0 = -4.4 \text{ V} \), \( C = 0.0015 \text{ uF} \), and \( I = 0.45 \text{ uA} \). Using these values yields \( t = 16.6 \text{ milliseconds} \). Assuming the multivibrator transistors, \( Q_2 \) and \( Q_3 \), were initially nonconducting, then after 16.6
milliseconds the multivibrator changes states with both transistors going into saturation. Capacitor $C_1$ then quickly discharges through the base-emitter diode of transistor $Q_2$ and the collector-emitter impedance of $Q_3$. This discharge time is approximately 10 microseconds. The short pulse appearing at the collector of $Q_3$ is then used to fire the laser. Since the multivibrator on-time is very short compared to the off-time, the on-time has little effect on the period.

The pulse period calculated above agrees quite closely with that measured in the laboratory.

F. Detector Signal to Noise Ratio

In order to determine whether or not to use lenses at the receiver and transmitter, it is necessary to calculate the signal to noise ratio at the receiver's optical detector output. Since only one receiver will be needed, it would be advantageous to concentrate on improving the S/N ratio at the receiver only if an acceptable S/N ratio can be obtained in this manner. In addition to increasing the system cost, placing a lens at the transmitter end to focus the laser beam would necessarily make it more difficult for the aircraft to hit the beam. If necessary, additional detectors and lens systems could be added at the receiver without greatly increasing the overall system cost. Also, since the laser diode optical output is concentrated at a wavelength of 0.9 microns, bandpass filters can be added to reduce noise power at the detector. The detector chosen for this receiver is a 100-PIN-RM diffused junction silicon photodiode manufactured by Solid State Radiation, Inc.
Figure 7 is a photograph of the PIN diode detector being used along with an integrated circuit video amplifier.

The first calculation of S/N ratio is for a system without lenses at either transmitter or receiver. If the aircraft flies at an altitude of 100 feet and the laser beam spread is 15 degrees, then at 100 feet the beam will have a diameter of 26.8 feet and an area of 544 feet\(^2\). The optical power density, for a laser output of 5 Watts, is

\[
P_o = \frac{5 \text{ W}}{544 \text{ ft}^2} = 9.2 \times 10^{-3} \text{ W/ft}^2
\]

at 100 feet from the laser diode. Now the detector's sensitive surface area is 0.155 in.\(^2\) or 1.08 \times 10^{-3} \text{ ft}^2\) so that the optical power present at the detector is

\[
P_{d} = 9.2 \times 10^{-3} \text{ W/ft}^2 \times 1.08 \times 10^{-3} \text{ ft}^2
\]

\[
= 9.94 \times 10^{-6} \text{ W.}
\]

The detector sensitivity at the laser wavelength of 0.9 microns is specified as 0.5 A/W. The detector is working into a load of 47 ohms shunted by 220 pF. The detector signal output current \(I_d\) is calculated from

\[
I_d = 0.5 \text{ A/W} \times 9.94 \times 10^{-6} \text{ W}
\]

\[
= 5.0 \times 10^{-6} \text{ A}
\]

and the power output is

\[
S_d = I_d^2 \times R
\]

\[
= (5.0 \times 10^{-6} \text{ A})^2 \times 47 \text{ ohms}
\]

\[
= 1.2 \times 10^{-9} \text{ W.}
\]

The detector noise output is specified as 4 \times 10^{-13} \text{ W/Hz}^{\frac{1}{2}}. The detector load has its upper 3dB point at
Figure 7  PIN Diode Photo Detector and Integrated Circuit Portion of Optical Receiver
$W_{3dB} = \frac{1}{RC}$

$= \frac{1}{220 \text{ pF} \times 47 \text{ ohms}}$

$= 9.7 \times 10^7 \text{ radians/second},$

or

$f_{3dB} = 1.54 \times 10^7 \text{ Hz},$

and the noise power at the detector output is

$N_d = 4 \times 10^{-13} \text{ W/Hz}^{\frac{1}{2}} \times (1.54 \times 10^7 \text{ Hz})^{\frac{1}{2}}$

$= 1.57 \times 10^{-9} \text{ W}.$

Therefore, the signal to noise ratio is

$(S/N)_d = \frac{1.2 \times 10^{-9} \text{ W}}{1.57 \times 10^{-9} \text{ W}}$

$= 0.74.$

This signal to noise ratio can be improved substantially by adding a 4 inch lens at the detector. This will increase the signal power present at the detector by a factor of approximately 80 and the detected signal output power by a factor of 6400. The factor of 6400 appears because the detected power output is proportional to $I_d^2$ and $I_d$ is directly proportional to the optical power present at the PIN diode. With a 4 inch lens the signal to noise ratio would then be

$(S/N)_d = 0.74 \times 6400,$

or approximately 37 dB. The above calculations do not account for the background noise power, but its effect can be minimized by utilizing a 0.9 micron filter at the receiver. The measurement of background noise power is one area that will require further consideration.
Figure 8 shows an infra red film photograph of the laser diode in operation. Other objects in the room emitting or reflecting infra red radiation can also be seen.
Laser Diode

Figure 8  Infra Red Film Photograph of Laser Diode. Exposure of 1.0 Second at F/2 taken in Optical Communications Laboratory
Experimental Results

A. Power Supply Circuit

The power supply portion of the transducer is shown in Figure 9. The parts of the power supply shown in this figure are the solar cell and battery charging circuit, the multivibrator DC to AC inverter, pulse amplifier, and voltage regulators.

Referring to Figure 9, Q5 is connected as a high efficiency rectifier between the solar cells and battery. The purpose of this rectifier is to prevent the battery from discharging through the solar cells on cloudy days or during nighttime hours. Transistors Q6 - Q8 sense the solar cell output voltage and if this voltage is not high enough, Q8 turns off the multivibrator consisting of Q10 - Q12 and associated components. Field effect transistor Q10 in the base circuit of Q12 turns the multivibrator off, when the voltage regulators are satisfied, to conserve power. A 55 Volt zener diode is connected from the output of the 60 V regulated power supply to the gate of Q10. When the output exceeds the zener breakdown voltage a large positive voltage is placed on the FET gate turning it off. This then stops the multivibrator. When the output voltage of the 60 V regulated supply drops the FET turns on again and the process is repeated. Thus the multivibrator does not run constantly but turns on only long enough to bring the output voltages up to the required level and then turns off. When the multivibra-
Figure 9  Five Volt and Sixty Volt Regulated Power Supply Circuit
tor is in the off condition, the current drain is reduced to 50 to 100 uA. This is accomplished by making $Q_{14}$ a PNP transistor so that $Q_{11}$, $Q_{13}$, $Q_{14}$, and $Q_{15}$ are all off at the same time, and only $Q_{12}$ is conducting. Transistors $Q_{13}$ and $Q_{14}$ amplify and shape the square wave signal from the collector of $Q_{12}$. The square wave output of $Q_{14}$ is used to drive transistor $Q_{15}$. The 10 mH inductor in the collector circuit of transistor $Q_{15}$ stores energy while $Q_{15}$ is on. When $Q_{15}$ turns off, this energy is transferred to the 1 uF capacitor through the 1N914 diode. This energy charges the 1 uF capacitor to 60 V. This 60 V is used to power the laser. When this voltage reaches the 60 V level the 55 V zener diode breaks down and controls the multivibrator as explained before. The voltage pulse developed at the collector of $Q_{15}$ is also connected to the low voltage regulator consisting of $Q_{9}$, $Q_{16}$ and associated components. This circuit is connected as a conventional series regulator. The 6.8 V zener diode in the base circuit of $Q_{9}$ sets the reference voltage for the regulator. The reference voltage is set at 6.8 V to compensate for the base-emitter voltage drops of the two transistors. The 68 pF capacitor is included to speed up the regulator circuit response. If the voltage at the emitter of $Q_{16}$ drops to less than approximately 5.4 V, the next pulse from the inductor turns $Q_{9}$ and $Q_{16}$ on to raise the emitter voltage of $Q_{16}$. Thus the output is regulated at 5.4 V. Since the low voltage regulator will conduct before the 1N914 diode in the 60 V regulator, the low voltage regulator is always satisfied first. After the low voltage regulator is satisfied, the remaining portion of the voltage pulse is used to satisfy the 60 V regulator. The 10 k resistor and the two 220 uF capacitors are used to
filter the 5 V regulated output.

B. Voltage to Pulse Repetition Rate Converter

The voltage to pulse repetition rate circuit functions to produce a pulse repetition rate proportional to the input voltage. The circuit is shown in Figure 10. $V_X$ is the input voltage which will be derived from the pipeline to ground potential. Transistors $Q_3$ and $Q_4$ are connected as a complementary astable multivibrator. Using this type of multivibrator results in $Q_3$ and $Q_4$ both being off at the same time and on at the same time. Since the on time is very short compared to the off time, current drain is consequently much lower than for a conventional multivibrator. In addition, the short duration positive output pulse is ideal for triggering the SCR in the laser circuit, which is to be considered next, since no pulse shaping is required. In operation, $Q_3$ and $Q_4$ are normally off. The 0.0015 uF capacitor is charged through transistor $Q_1$ and the 2.2 Megohm emitter resistor. $Q_1$ can be thought of as a constant current source whose current is controlled by the input voltage $V_X$. As the 0.0015 uF capacitor is charged by the constant current source, a point is reached where $Q_3$ begins to conduct, thus lowering its collector voltage. This collector voltage is coupled to the base of transistor $Q_4$ which also begins to conduct, raising its collector voltage. Since the collector of $Q_4$ is coupled to the base of $Q_3$ through the charging capacitor, $Q_3$ is forced to conduct even more, so that both transistors quickly go into saturation. This type of circuit action is termed regeneration. With both transistors in saturation the 0.0015 uF capacitor quickly (15 usec) charges in the opposite direction
Figure 10 Voltage to Pulse Repetition Rate Circuit and Laser Driving Circuit
through the low impedance of the emitter-collector circuit of $Q_4$ and the emitter-base diode of $Q_3$. When the capacitor has charged to approximately 4 V, regenerative action again occurs and both transistors turn off. $Q_2$ is included in the circuit for temperature compensation. The short duration pulse at the collector of $Q_4$ is coupled to the laser circuit which is to be discussed next.

C. Laser and Firing Circuit

The function of the laser firing circuit is to convert the pulse repetition rate to an optical output with repetition rate of the same frequency. This circuit is shown in Figure 10.

In operation, the 0.02 μF capacitor is charged from the 60 V supply through the 150 k resistor, and the 1N914 diode in parallel with the LD 63 laser diode. The 150 k resistor is chosen small enough so that the capacitor charges to the full supply voltage between pulses, but not so small as to allow the SCR to become latched on after the gate pulse is removed. When a pulse is coupled to the gate of the SCR, the SCR turns on, discharging the capacitor through the LD 63 laser diode. The SCR chosen for this application is a GA 201 manufactured by Unitrode Corporation in Watertown, Massachusetts. This SCR is a high speed unit with a turn on time of 20 nanoseconds typical, and a peak forward current of 50 A for 10 microseconds. As stated in the section on theoretical considerations, the capacitor discharges in approximately 200 nanoseconds, so that the capacitor completely discharges through the laser diode. The peak current through the laser diode approaches 25 A. Due
to this high current level and associated inductive spikes in the circuit, the 1N914 diodes are included to prevent high reverse voltages across the SCR and laser diode, which is sensitive to reverse voltages. The 1N914 diode across the laser diode therefore serves a dual purpose, i.e., charging the 0.02 uF capacitor and preventing damage to the laser diode.

D. Receiver Preamplifier

Figure 11 shows the preliminary circuit for a receiver optical detector and preamplifier. The PIN diode detector is used in this circuit in a reverse biased mode since its maximum sensitivity to light changes is in this mode of operation. When light strikes the PIN diode, the resultant current change in the PIN diode is coupled through a 0.01 uF capacitor to the 47 ohm resistor. The voltage developed across the resistor is amplified by the first video amplifier. The gain of this stage is 100. The output of the first amplifier is further amplified by the second video amplifier operating with a gain of 10. The output of this amplifier can then be used to trigger a counter to give pulse rate information, or be further processed.

Lenses are expected to be used with the receiver to improve the signal to noise ratio, and in addition, some optical filtering may be required to reduce the noise present at the detector. No lens system is expected to be needed at the transmitter. This is desirable since only one receiver will be required and it can be quite complex, whereas many transmitters will be used.
Figure 11  Preliminary Circuit for Optical Receiver

(Photo Diode and Amplifier Portion Only)
Conclusion

The component side of the prototype circuit board is shown in Figure 12 and the solar cell side is shown in Figure 13. Figures 14 and 15 show the corresponding printed circuit version of the solid state transducer. The circuit has been tested over the temperature range of 70° F to 150° F with a pulse period change of 1%. Tests from 32° F to 70° F indicate a pulse period change of 7% and tests from -13° F to 32° F produce an additional change of 7%. These latter changes will need to be accounted for in the calibration of the unit. The only calibration necessary in production will be the pulse period calibration. The circuit has no other adjustments to be performed. In addition, close tolerance components are not utilized in the solid state transducer. This should greatly reduce the overall production costs.

Research on this project provided for some interesting observations. In the early stages of the project while attempting to power a DC to AC inverter from the 0.85 V pipeline potential, the author found that a multivibrator utilizing germanium transistors and driving an inductive load could be made to reliably oscillate with a power source as low as 0.1 V. Another interesting circuit developed for this project is the power supply section which charges a capacitor from the energy stored in the 10 mH inductor. This circuit can theoretically supply any regulated voltage desired by changing the value of one zener diode.
Figure 12  Circuit Side of Prototype Solid State Transducer
Figure 13  Solar Cell - Battery Side of Prototype Solid State Transducer
Figure 14  Printed Circuit Version (Component Side) of
Solid State Transducer
Figure 15  Printed Circuit Version (Solar Cell Side) of
Solid State Transducer and Enclosure
Throughout this project, emphasis was placed on low power consumption. As a result, the end product is a laser transmitter which can be modulated and which will operate continuously for one month on a 1.25 V flashflight battery without recharging. Utilizing the solar cells for charging the solid state transducer should operate in excess of five years.
LIST OF REFERENCES


