Photometer and Optical Link

Purpose
You will design and build a photometer (optical detector) based on a silicon photodiode and a current-to-voltage amplifier whose output is proportional to the intensity of incident light. First you will use it to measure the room light intensity. Then you will set up and investigate an optical communication link in which the transmitter is a light emitting diode (LED) and the receiver is your photodiode detector.

Introduction
Experiment 8 demonstrates the use of special p-n junction diodes in reverse bias as a detector of light. The incoming radiation energy excites electrons across the silicon band gap, producing a current or a pulse of charge proportional to the incident energy deposited in the detector.

In this experiment we will introduce a number of new "photometric" quantities that are widely used in opto-electronics. At the end of the lab, you will use a "lock-in" amplifier to extract a weak signal from noise.

Readings
For general background on opto-electronics, see H&H Section 9.10. All of the detailed information you will need for this experiment is given in the write-up.

New Apparatus and Methods

PHOTODIODE
The MRD500 photodiode used in this experiment is a p-intrinsic-n (PIN) silicon diode operated in reverse bias. A sketch if the photodiode structure is shown in Figure 8a.1. The very thin p-type conducting layer acts as a window to admit light into the crystal. The reverse bias voltage maintains a strong electric field throughout the intrinsic region forming an extended depletion layer. The depletion layer should be thicker than the absorption length for photons in silicon in order to maximize the efficiency. Any incident photon whose energy exceeds the band-gap energy is absorbed to produce an electron-hole pair by photoelectric excitation of a valence electron into the conduction band. The charge carriers are swept out of the crystal by the internal electric field to appear as a photocurrent at the terminals. The photocurrent is proportional to the rate at which light is entering the diode.
LIGHT EMITTING DIODE
The photodiode acts electrically just like any diode. It emits light when forward-biased due to direct radiative recombination of electrons and holes. The forward voltage drop is about 1.7 V rather than 0.6 V because the LED is made of GaAsP instead of silicon.

LOCK-IN AMPLIFIER
The lock-in amplifier is an AC voltmeter which is sensitive to signals as small as a nanovolt. To achieve this sensitivity, it must be given the phase and frequency of the expected signal. Imagine that signal to be a very small square wave which is buried in noise. If you knew beforehand exactly when the positive going portion of the wave should occur, you could throw a switch (electronically) to charge one plate of an integrating capacitor positively, the other negatively. Of course, after only 1/2 cycle the accumulated charge is very small; because of the noise, it might even be of the wrong sign. On the next half cycle you reverse the switch, shunting the expected positive charge to the same plate as before. Keep reversing the switch every half cycle. Eventually a signal which is in phase with the expected one will build a sensible DC level on the capacitor. Noise will average to zero.
**Theory**

**CURRENT-TO-VOLTAGE AMPLIFIER**

In an ordinary inverting amplifier (Figure 5.1) the input voltage is applied to a resistor, and the amplifier generates an output voltage in response to the current that flows through the input resistor to the virtual ground at the negative op-amp input. A current-to-voltage amplifier (Figure 8a.2) is an inverting amplifier with the input current $I_{in}$ applied directly to the negative op-amp input. Since no current flows into the op-amp input, the output voltage must be $V_{out} = -I_{in}R_F$. The ideal low-frequency gain of a current-to-voltage amplifier is

$$G = \frac{V_{out}}{I_{in}} = -R_F.$$  

This gain has the units of impedance, and it is often called a trans-impedance. The current-to-voltage amplifier is called a trans-impedance amplifier.

**PHOTODIODE SENSITIVITY**

The sensitivity $S_\lambda$ (in units of $\mu A/(mW/cm^2)$) is defined as the photocurrent per unit light intensity incident on the photodiode. It is a function of the light wavelength $\lambda$. Thus for light intensity $N$ (in mW/cm²) the photocurrent $I$ (in $\mu A$) is given by

$$I = S_\lambda N.$$  

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**Figure 8a.2  Light transmitter and photodiode detector**

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The sensitivity at any wavelength $\lambda$ is given on the data sheet in terms of the peak sensitivity at 800 nm times a correction factor called the relative spectral response, or RSR:

$$S_\lambda = S_{(800 \text{ nm})} \text{ RSR}(\lambda).$$  \hspace{1cm} (3)

**LED OUTPUT**

To describe the output of an approximate point source like our photodiode, it is helpful to introduce the notion of solid angle. Consider a transparent sphere of radius $d$, and suppose that an area $A$ on the surface of the sphere is painted black. We then say that the blacked out region subtends a solid angle of $\Omega$ steradians, where $\Omega = A/d^2$. According to this definition the whole sphere subtends a solid angle of $4\pi$ str.

The concept of solid angle is essential in separating the two units in which light is customarily measured. Both the lumen and the candela originated in the 18th century when the eye was the primary detector of electromagnetic radiation.

The lumen (lm) is to light what the watt is to E & M. It is a measure of luminous flux (rather than radiant flux). A standard 100-watt light bulb produces 1710 lm. The bulb is not very efficient. If all its output were concentrated at the yellow-green color to which our eyes are most sensitive, the bulb would produce $100 \text{ W} \times 683 \text{ lm/W} = 68300 \text{ lm}$. The mysterious factor "683" is an official summary of measurements made in the 1930's. In a very thorough experiment, colorblind subjects were asked to compare the perceived brightness of sources of differing wavelengths and known radiant strengths.

The results of this experiment are expressed by the formula

$$F(W) = F(\text{lm})/\{683*\text{RR}(\lambda)\}$$  \hspace{1cm} (4a)

In this formula the dimensionless number $\text{RR}(\lambda)$ is called the relative response of the adjusted human eye. A rough plot of $\text{RR}(\lambda)$ is shown in Figure 8.3.
For historical reasons, illumination engineers have also retained a cousin of the lumen, the candela. The candela, which is the same as the lumen per steradian, measures luminous intensity IN A PARTICULAR DIRECTION. Both the candela and the lumen are best illustrated by imagining a standard candle as an isotropic source of light. The candle emits a total of $4 \pi$ lumens which is 1 lm/sr or 1 cd in all directions. Place a mirror right behind the candle. The luminous flux is still $4 \pi$ lm, but the luminous intensity is now 2 cd in front of the mirror (and 0 cd behind).

We now rewrite the last equation as a relation between radiant and luminous intensities:

$$J (\text{mW/str}) = \frac{1.464 \cdot 10^{-3}}{RR(\lambda)} J (\text{mcd}).$$

(4b)

Suppose now we place our photodiode a distance d from the LED, and we want to find the intensity H (mW/cm²) at the photodiode. We first find $J$ in millicandela on the LED data sheet. The data sheet will give the dependence of $J$ (mcd) on the diode current and on direction. We then convert $J$ (mcd) to $J$ (mW/str), using Equation 4 and $RR(\lambda)$ for the appropriate wavelength. (For our LED, $RR(635 \text{ nm})=0.2$.) Finally we divide $J$ (mW/str) by $d^2$ to get H (mW/cm²).

**Outline of the Experiment**

1. Design and build a photometer with sensitivity of about 10 Volts/(mW/cm²), using a photodiode and a current-to-voltage amplifier.

Figure 8.3 Relative response of adjusted human eye.

![Relative Response](image)
2. With the photodiode covered to keep out light, test and calibrate the amplifier using a test current source.

3. Measure the light intensity in the lab, and compare with sunlight. Compare the calibration of your photometer with the Tektronix reference photometer and with the design sensitivity.

4. Set up an optical communication link in which the transmitter is a light emitting diode driven by the function generator and the receiver is your photodetector. Place the LED close to the photodiode to begin with, and compare the received signal strength with your predicted value.

5. What is the greatest distance you can transmit identifiable signals?

Problems
1. Estimate the sensitivity $S_{\lambda}$ (in units of $\mu$A/(mW/cm$^2$)) of the MRD 500 photodiode to the fluorescent lights in the lab. See the photodiode data sheet in the Appendix. You will have to estimate the mean wavelength of the white fluorescent light. See Figure 8a.3.

2. For the current-to-voltage amplifier in Figure 8a.2, choose a value for the feedback resistor $R_F$ so that an incident white-light intensity $H$ of 1.0 mW/cm$^2$ produces an output voltage of 10 V. The small feedback capacitor $C_F$ is used to suppress spontaneous oscillations. The bandwidth will suffer if $C_F$ is too large. What is the bandwidth $f_B$ if $C_F = 10$ pF? Use the formula $f_B=1/(2\pi R_F C_F)$.

3. Write down the dc values of the voltages at the + and − inputs and at the output of the op-amp for zero light on the photodiode. What would the voltages be if the photodiode leads were accidentally reversed to make it forward biased?

4. For the light transmitter in Figure 8a.2, compute the intensity $H$ (in units of mW/cm$^2$) of light incident on a detector 5 cm away placed at the center of the transmitted beam. Assume there is a current of 30 mA flowing through the LED. See Appendix for LED data. Compute the expected output voltage from the optical receiver under these conditions. Remember to recalculate the sensitivity of the detector for the wavelength of light from the LED.
5. The transmitter will generate square waves. The high-level should give 30 mA forward
current in the LED, and the low level should give 0 mA. These two levels should
correspond to 15 V and 0 V unloaded output from the function generator. Find the value of
the series resistor $R_s$ that gives the correct current. Look on the data sheet to find the LED
forward voltage drop at 30 mA. Do not forget that when the unloaded output of the
function generator is set to 15 V, the loaded output will be lower because of the 50 $\Omega$ output
impedance.

**Procedure**

**PHOTOMETER**

Build the photometer circuit shown in Figure 8a.2. Null the op-amp output voltage by adjusting the
25 k$\Omega$ trimpot when the photodiode is blacked out and the input test current set to zero.

Test the amplifier using the test current source ($R_T$ and the function generator) with the photodiode
still covered. Verify that the ac gain for 1 kHz square waves is correct. If the amplifier goes into
spontaneous oscillations, suppress these with a few pF of trimming capacitor $C_F$ across the
feedback resistor. Set the test current to zero and uncover the photodiode.

Measure the average intensity of light from the fluorescent lamps in the lab. The intensity of solar
radiation on a clear day is about 1 kW/m$^2$. What fraction of this is the average light intensity in the
lab? Compare the reading of you photometer with the reading from the Tektronix light meter. We
recommend that you aim both the photodiode and the Tektronix meter at a sheet of white paper
placed flat on the bench which is well exposed to the room light. Does your photometer have the
sensitivity you predicted?

**OPTICAL COMMUNICATION LINK**

Set up a light emitting diode type MV5752 as the transmitter on a separate small circuit board and
drive it with the signal generator. Be sure to protect the LED with a series resistance that prevents
the forward current exceeding 30 mA. Also connect a rectifier diode in parallel with the LED but
with opposite polarity, to prevent negative voltage excursions that can break down the LED if
greater than 5 volts. Place the LED transmitter 5 cm from the photodiode and orient both elements
to be coaxial so as to maximize the amount of light detected.

Drive the transmitter with 1 kHz square waves from the generator, using the dc offset to keep the
output above ground. Observe the input driving signal and the output of the receiver on the scope using dc coupling for both signals initially. Make sure the received signal is due to the red light by blocking the beam for a moment. If there is overshoot on the leading edge of the square wave, you can trim it out with a few pF of capacitance across $R_F$. A pair of twisted insulated wires makes a convenient capacitance (about 0.5 pF per twist—check it on the capacitance meter).

Measure the intensity of the transmitted light and compare with your prediction. Examine the rise time of the received square waves. From this, estimate the upper 3dB bandwidth of the communication link.

LOCK-IN AMPLIFIER
Finally attach the lock-in amplifier in parallel with the scope. For the signal input to the lock-in, choose CHANNEL A and set the adjacent switch accordingly. Trigger the lock-in by running a cable from the TRIG OUTPUT of your function generator to the REFERENCE INPUT of the lock-in amplifier. Set the switches above this input to "I" and "positive square". You should then find that you get maximum output when the phase is close to 90 degrees. Don't worry about the other switches on the lock-in. Their operation will become clear when you begin to detect a signal.

Work with the room lights on and a signal frequency of around 1 kHz.

What is the smallest signal you can detect on the scope?

What is the smallest signal you can detect on the lock-in?
Appendix

Data sheet for the Motorola MRD500 photodiode.

MOTOROLA
SEMICONDUCTOR
TECHNICAL DATA

Photo Detectors
Diode Output

...designed for application in laser detection, light demodulation, detection of visible and near infrared light-emitting diodes, shaft or position encoders, switching and logic circuits, or any design requiring radiation sensitivity, ultra high-speed, and stable characteristics.

- Ultra Fast Response — (<1 ns Typ)
- High Sensitivity — MRD500 (1.2 μA/mW/cm² Min)
  MRD510 (0.3 μA/mW/cm² Min)
- Available With Convex Lens (MRD500) or Flat Glass (MRD510) for Design Flexibility
- Popular TO-18 Type Package for Easy Handling and Mounting
- Sensitive Throughout Visible and Near Infrared Spectral Range for Wide Application
- Annular Passivated Structure for Stability and Reliability

MAXIMUM RATINGS (T A = 25°C unless otherwise noted)

<table>
<thead>
<tr>
<th>Rating</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reverse Voltage</td>
<td>V R</td>
<td>100</td>
<td>Volts</td>
</tr>
<tr>
<td>Total Power Dissipation @ T A = 25°C</td>
<td>P D</td>
<td>250</td>
<td>mW</td>
</tr>
<tr>
<td>Derate above 25°C</td>
<td></td>
<td>2.27</td>
<td>mW°C</td>
</tr>
<tr>
<td>Operating Temperature Range</td>
<td>T A</td>
<td>-55 to -125</td>
<td>°C</td>
</tr>
<tr>
<td>Storage Temperature Range</td>
<td>T sig</td>
<td>-65 to -150</td>
<td>°C</td>
</tr>
</tbody>
</table>

STATIC ELECTRICAL CHARACTERISTICS (T A = 25°C unless otherwise noted)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Fig. No.</th>
<th>Symbol</th>
<th>Min</th>
<th>Typ</th>
<th>Max</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dark Current (V R = 20 V, R L = 1 megohm) Note 2</td>
<td>2 and 3</td>
<td>I D</td>
<td>—</td>
<td>2</td>
<td>nA</td>
<td></td>
</tr>
<tr>
<td>Reverse Breakdown Voltage (I R = 10 μA)</td>
<td>—</td>
<td>V BR/R</td>
<td>100</td>
<td>200</td>
<td>—</td>
<td>Volts</td>
</tr>
<tr>
<td>Forward Voltage (I P = 50 mA)</td>
<td>—</td>
<td>V F</td>
<td>—</td>
<td>1.1</td>
<td>Volts</td>
<td></td>
</tr>
<tr>
<td>Series Resistance (I P = 50 mA)</td>
<td>—</td>
<td>R S</td>
<td>—</td>
<td>10</td>
<td>Ohms</td>
<td></td>
</tr>
<tr>
<td>Total Capacitance (V R = 20 V, f = 1 MHz)</td>
<td>5</td>
<td>C T</td>
<td>—</td>
<td>4</td>
<td>pF</td>
<td></td>
</tr>
</tbody>
</table>

OPTICAL CHARACTERISTICS (T A = 25°C unless otherwise noted)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>MRD500</th>
<th>1</th>
<th>I L</th>
<th>6</th>
<th>9</th>
<th>2.1</th>
<th>—</th>
<th>—</th>
<th>—</th>
<th>—</th>
<th>μA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Current</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>(V R = 20 V)</td>
<td>Note 1</td>
<td>MRD500</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>μA/mW/cm²</td>
</tr>
<tr>
<td>Sensitivity at 0.8 μm</td>
<td>—</td>
<td>S (λ = 0.8 μm)</td>
<td>—</td>
<td>6.6</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>μA/mW/cm²</td>
</tr>
<tr>
<td>(V R = 20 V) Note 3</td>
<td>MRD510</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>1.5</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>μA/mW/cm²</td>
</tr>
<tr>
<td>Response Time</td>
<td>—</td>
<td>τ (resp)</td>
<td>—</td>
<td>1</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>(V R = 20 V, R L = 50 Ohms)</td>
<td>—</td>
<td>L</td>
<td>—</td>
<td>0.8</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td></td>
</tr>
</tbody>
</table>

NOTES: 1. Radiation Flux Density (H) equal to 5 mW/cm² emitted from a tungsten source at a color temperature of 2870 K.
2. Measured under dark conditions; (H = 0).
3. Radiation Flux Density (H) equal to 0.5 mW/cm² at 0.8 μm.

Experiment # 8

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TYPICAL CHARACTERISTICS

Figure 1. Irradiated Voltage — Current Characteristic

Figure 2. Dark Current versus Temperature

Figure 3. Dark Current versus Reverse Voltage

Figure 4. Capacitance versus Voltage

Figure 5. Relative Spectral Response
Data sheet for the General Instrument MV5752 red LED.

<table>
<thead>
<tr>
<th>ORANGE</th>
<th>MV5152</th>
<th>MV6152</th>
</tr>
</thead>
<tbody>
<tr>
<td>YELLOW</td>
<td>MV5352</td>
<td>MV6352</td>
</tr>
<tr>
<td>HIGH EFFICIENCY GREEN</td>
<td>MV5452</td>
<td>MV6452</td>
</tr>
<tr>
<td>HIGH EFFICIENCY RED</td>
<td>MV5752</td>
<td>MV6752</td>
</tr>
</tbody>
</table>

**PACKAGE DIMENSIONS**

<table>
<thead>
<tr>
<th>MV5X52</th>
<th>LEAD CUT CATHODE LONG MIN. 0.8”</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV6X52X</td>
<td>LEAD CUT ANODE LONG MIN. 1.025”</td>
</tr>
</tbody>
</table>

**DESCRIPTION**

These Clear Tinted solid state indicators offer high brightness and color availability. The High Efficiency Red and Yellow devices are made with gallium arsenide phosphide on gallium phosphide. The High Efficiency Green units are made with gallium phosphide on gallium phosphide. All devices are available with cathode long as MV5X5X, or with anode long as MV6X5X.

**FEATURES**

- High on-axis light output
- High efficiency GaP light sources
- Versatile mounting on PCB board or panel
- Snap in grommet MPS2 available as separate order item
- Long life—solid state reliability
- Low power requirements
- Compact, rugged, lightweight

**ABSOLUTE MAXIMUM RATINGS** ($T_A = 25^\circ C$ Unless Otherwise Specified)

<table>
<thead>
<tr>
<th>Red, Yellow</th>
<th>Red, Yellow</th>
<th>Green</th>
</tr>
</thead>
<tbody>
<tr>
<td>AND H. E. RED</td>
<td>AND H. E. RED</td>
<td>GREEN</td>
</tr>
<tr>
<td>Power dissipation</td>
<td>120 mW</td>
<td>120 mW</td>
</tr>
<tr>
<td>Derate linearly from 25°C (MV452/4A from 50°C)</td>
<td>1.6 mW/°C</td>
<td>1.6 mW/°C</td>
</tr>
<tr>
<td>Storage and operating temperatures</td>
<td>-55°C to +100°C</td>
<td>-55°C to +100°C</td>
</tr>
<tr>
<td>Lead soldering time at 260°C (See Note 3)</td>
<td>5 sec.</td>
<td>5 sec.</td>
</tr>
<tr>
<td>Continuous forward current</td>
<td>35 mA</td>
<td>30 mA</td>
</tr>
<tr>
<td>Peak forward current (1 μsec pulse, 0.3% duty cycle)</td>
<td>1 A</td>
<td>90 mA</td>
</tr>
<tr>
<td>Reverse voltage</td>
<td>5 V</td>
<td>5 V</td>
</tr>
</tbody>
</table>

**PHYSICAL CHARACTERISTICS**

<table>
<thead>
<tr>
<th>Cathode</th>
<th>Anode</th>
<th>Source Color</th>
<th>Lens Type</th>
<th>Lens Effect</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV5152</td>
<td>MV6152</td>
<td>High Efficiency Red</td>
<td>Amber Clear</td>
<td>Point Source</td>
<td>Backlighting</td>
</tr>
<tr>
<td>MV5352</td>
<td>MV6352</td>
<td>Yellow</td>
<td>Yellow Clear</td>
<td>Point Source</td>
<td>Backlighting</td>
</tr>
<tr>
<td>MV5452</td>
<td>MV6452</td>
<td>High Efficiency Green</td>
<td>Green Clear</td>
<td>Point Source</td>
<td>Backlighting</td>
</tr>
<tr>
<td>MV5752</td>
<td>MV6752</td>
<td>High Efficiency Red</td>
<td>Red Clear</td>
<td>Point Source</td>
<td>Backlighting</td>
</tr>
</tbody>
</table>

Experiment # 8

8.11	Fall 1999
ELECTRO-OPTICAL CHARACTERISTICS (25°C Free Air Temperature)

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>TEST COND.</th>
<th>UNITS</th>
<th>MV5152</th>
<th>MV5352</th>
<th>MV5452</th>
<th>MV5451</th>
<th>MV5752</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward voltage (Vf) typ.</td>
<td>If = 20 mA</td>
<td>V</td>
<td>2.0</td>
<td>2.1</td>
<td>2.2</td>
<td>2.2</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>If = 20 mA</td>
<td>V</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>Luminous Intensity (See Note 1)</td>
<td>If = 20 mA</td>
<td>mcd</td>
<td>17.0</td>
<td>10.0</td>
<td>12.0</td>
<td>30.0</td>
<td>17.0</td>
</tr>
<tr>
<td>typ.</td>
<td>If = 20 mA</td>
<td>mcd</td>
<td>40.0</td>
<td>45.0</td>
<td>25.0</td>
<td>60.0</td>
<td>40.0</td>
</tr>
<tr>
<td>Peak wavelength</td>
<td>If = 20 mA</td>
<td>nm</td>
<td>635</td>
<td>585</td>
<td>562</td>
<td>562</td>
<td>635</td>
</tr>
<tr>
<td>Spectral line half width</td>
<td>If = 20 mA</td>
<td>nm</td>
<td>45</td>
<td>35</td>
<td>30</td>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td>Capacitance typ.</td>
<td>V = 0, f = 1 MHz</td>
<td>pF</td>
<td>45</td>
<td>45</td>
<td>20</td>
<td>20</td>
<td>45</td>
</tr>
<tr>
<td>Reverse voltage (Vr) min.</td>
<td>Ir = 100 μA</td>
<td>V</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Reverse current (Ir) max.</td>
<td>Vr = 5.0 V</td>
<td>μA</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Viewing angle (total)</td>
<td>See Fig. 4</td>
<td>degrees</td>
<td>28</td>
<td>28</td>
<td>35</td>
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</tbody>
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TYPICAL ELECTRO-OPTICAL CHARACTERISTIC CURVES (25°C Free Air Temperature Unless Otherwise Specified)

NOTES
1. As measured with Photo Research Corp. “SPECTRA” Microcandela Meter (Model IV-D).
2. The axis of spatial distribution are typically within a 10° cone within reference to the central axis of the device.
3. The leads of the device were immersed in molten solder, at 260°C, to a point 1/16 inch (1.6 mm) from the body of the device per MIL-S-750, with a dwell time of 5 seconds.

Experiment # 6  8.12  Fall 1999