LOC Series
Linear Optocouplers

Application Note: AN-107

INTEGRATED CIRCUITS DIVISION

1   Introduction

This application note describes isolation amplifier design principles for the LOC Series linear optocoupler devices. It describes the circuit operation in photoconductive and photovoltaic modes and provides some examples of applications in different industry segments. The LOC product is intended to give the designer an alternative to bulky transformers and "non-linear" optocouplers for many applications.

Galvanic isolation is required for many circuits found in Telecommunication, Industrial, Medical and Instrumentation systems. This has been traditionally accomplished by means of transformers and optocouplers, with transformers being used to couple AC signals and optocouplers used primarily for DC signal coupling. Unlike standard optocouplers, the LOC operates in a servo mode configuration which compensates for the LED's non-linear time and temperature characteristics. In addition, the LOC can couple both AC and DC signals.

The following are examples in which galvanic isolation is required:

- **Telecommunications:** Telecom products such as modems require isolation and signal coupling from the telephone line to the modem data pump.
- **Industrial Control:** Products such as temperature sensors and controllers. Temperature sensors are often remote from the controller, residing in hazardous environments near high voltage. Isolation provides the required signal coupling while insuring safety to personnel working with the controller.
- **Medical:** EEG and ECG machines have sensors that attach to the patient. The sensors are galvanically isolated to provide a high voltage isolation barrier between patient and machine.
- **Instrumentation:** Instruments often use isolated switching supplies where it is required to sense the output voltage and feed back a portion of the signal to the controller for voltage regulation while not compromising power supply isolation.

2   Description

The LOC Series (LOC110, LOC111 and LOC112 with one optocoupler per package, and LOC210 and LOC211P with two per package) are linear optocouplers designed to be used in applications where galvanic isolation is required for AC and DC signal coupling and linearity from input to output must be accurately preserved. The device consists of an infrared LED optically coupled to two phototransistors.

One phototransistor is typically used in a servo feedback mechanism to control the LED drive current which has the effect of compensating for the LED's non-linear time and temperature characteristics. The other output phototransistor is used to provide the galvanic isolation between the input and output circuit. A typical isolating amplifier is shown in **Figure 1**.

3   Circuit Operation Utilizing the LOC110

3.1   Photoconductive Operation

With V_{IN} at 0V and I_F at 0mA, U1 has large open loop gain. As V_{IN} begins to increase, the output of U1 begins to go to the V_{CC1} rail. As it does, I_F current begins to flow and the LED begins to turn on. As the LED turns on, the incident optical flux on the servo phototransistor causes a current, I_1, to flow. As I_1 flows through R1, a voltage is developed on the inverting input of the op-amp V_A such that the output of the amplifier will begin to go to the negative supply rail (ground in this case). When the voltage on V_A is equal to V_{IN}, I_F will no longer increase and the circuit is now

in a stable closed loop condition. If V_{IN} is modulated, V_A will track V_{IN}. The flux generated by the LED is also incident on the output phototransistor and generates a current I_2 which is proportional to the LED flux and LED current; this current closely tracks I_1. The output voltage of the amplifier is the product of the output photocurrent I_2 and resistor R2. The equations and definitions of the circuit are listed below (including **Figure 1**).

Servo Gain - K1:

Defined as the ratio of the servo photocurrent I_1 to the LED forward current I_F: $K1 = I_1/I_F$

For the LOC110, K1 is typically 0.007 for an I_F of 10mA and a V_{CC} of 15V.

Forward Gain - K2:

Defined as the ratio of the output photocurrent to the LED forward current I_F: $K2 = I_2/I_F$

K2 is typically 0.007 for an I_F of 10mA and V_{CC} of 15V.

Transfer Gain - K3:

Defined as the ratio of K2 to K1: $K3 = K2/K1$.

3.2   Design Example: (See Figure 1)

For an input span of 0 to 2V, an output of 0 to 4V is desired. Values for R1 and R2 need to be determined. Both amplifiers will have an independent V_{CC} of +5V.

Determining R1:

Since the product of the servo photocurrent, I_1, and R1 will track V_{IN}:

1. $V_{IN} = I_1 \bullet R1$

Now I_1 is the photocurrent generated by the LED flux. The LED flux is generated by the LED current I_F . I_1 is proportional to I_F and the LED flux by the proportionality constant K1, which has been defined as the servo gain:

2. $I_1 = K1 \bullet I_F$

To best determine R1, the maximum desired value of I_F should be used in the above equation that would correspond to a maximum V_{IN} of 2V. For this example

an op-amp output of 15mA is selected. Substituting equation #2 for I_1 in equation #1 and solving for R1 yields:

3. $R1 = \dfrac{V_{IN}}{(K1 \bullet I_F)}$

Using the minimum value of 0.004 for K1 and substituting 2V for V_{IN} and 15mA for I_F (max.) gives a value of 33.3KΩ.

Determining R2:

The output voltage V_{OUT} is related to R2:

4. $V_{OUT} = I_2 \bullet R2$

Photocurrent I_2 is proportional to the LED flux and LED current I_F by the proportionality constant K2:

5. $I_2 = I_F \bullet K2$

Substituting equation #5 for I_2 in #4 and solving for R2:

6. $R2 = \dfrac{V_{OUT}}{(I_F \bullet K2)}$

where I_F=15mA, using the minimum value of K2 = 0.004, V_{OUT} = 4V.

Substituting the above values gives an R2 of 66.6KΩ.

The amplifier will produce a 4V output when a 2V input is applied. A plot of V_{IN} vs. V_{OUT} is shown in **Figure 2**. Photoconductive amplitude and phase response is shown in **Figure 3**.

The following derivation ties the example and definitions to one equation relating all the parameters for this circuit:

Solving equation #3 for V_{IN}:

7. $V_{IN} = I_F \bullet K1 \bullet R1$

Figure 1   Isolation Amplifier (Photoconductive Operation)
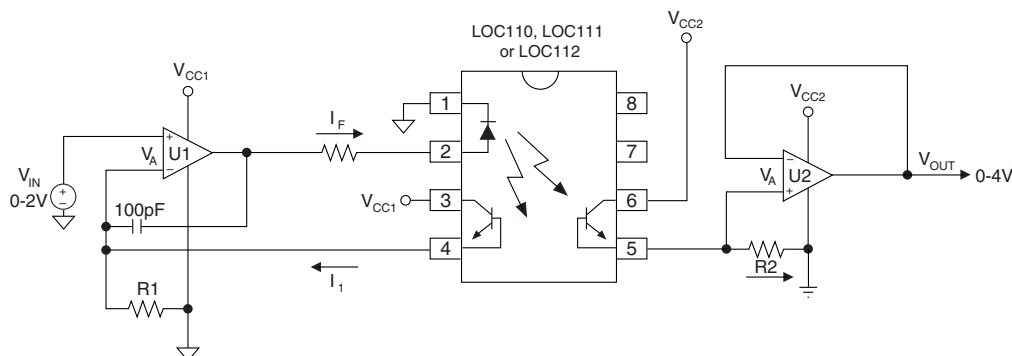
Combining equation #4 and #5 and solving for V_{OUT}:

8. $\quad V_{OUT} = I_F \bullet K2 \bullet R2$

Dividing equation #8 by equation #7 and solving for V_{OUT} gives the final equation:

9. $\quad V_{OUT} = \dfrac{V_{IN}\,(K2 \bullet R2)}{(K1 \bullet R1)}$

Since the definition of K3 is K3 = K2/K1 we can further simplify by writing:

10. $\quad V_{OUT} = V_{IN} \bullet K3 \bullet \dfrac{R2}{R1}$

I_F was canceled out of equation #9. This is due to the fact that both servo and output photocurrents originate from the same LED source. Since K3 is the ratio K2/K1, in our example K1 = K2 = 0.004, and K3 = 1.

Therefore, V_{OUT} is directly proportional to the ratio of R2/R1.
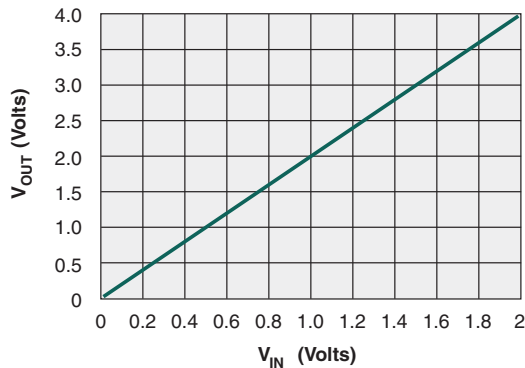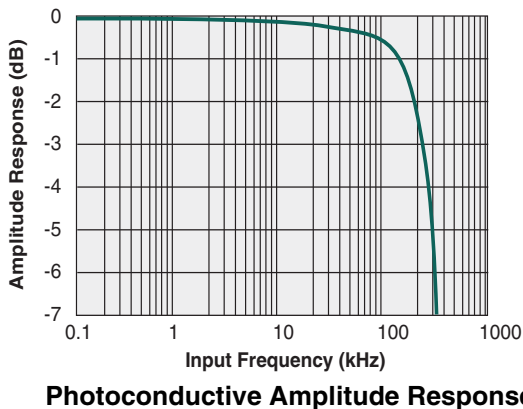
Figure 2 V_{IN} vs. V_{OUT}

The circuit in **Figure 1** is configured with the phototransistor collector to base reverse biased. This is operation in the photoconductive mode. When an application requires amplifier bandwidth of up to 200kHz, the photoconductive configuration should be used. This mode has linearity and drift characteristics comparable to an 8-bit D/A converter with ±1 bit linearity error.
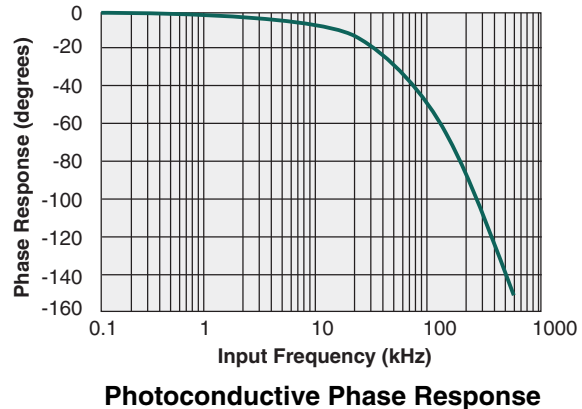
3.3   Photovoltaic Mode

Using the LOC product in the photovoltaic mode achieves the best linearity, lowest noise and drift performance. It is possible to achieve up to 14-bit D/A linearity in this mode. The trade-off with this topology is that bandwidth is limited to about 40KHz. A typical isolation amplifier in the photovoltaic configuration is shown in **Figure 4**.

In the photovoltaic mode, the LOC phototransistors act as current generators. Since all photogenerators display some voltage dependence on linearity, maintaining a 0V bias on the phototransistor eliminates this problem and improves linearity. If the phototransistor is connected across a small resistance, the output current is linear with increases in incident LED flux. To accomplish this, the phototransistors are connected across the op-amp inputs. As V_{IN} increases, the current through the LED increases and so does the optical flux. The LED flux is incident on the servo phototransistor which starts current I1 to flow from the op-amp inverting input through the phototransistor. This servo photocurrent is linearly proportional to:

11. $\quad V_{IN}, \; I1 = V_{IN}/R1$

and keeps the voltage on the inverting input equal to zero.

Figure 3   Photoconductive Amplitude Response and Phase Response

Photoconductive Amplitude Response

Photoconductive Phase Response

Figure 4   Isolation Amplifier (Photovoltaic Operation)

The flux from the LED is also incident on the output phototransistor which causes a current, I_2, to flow from the inverting input of the output op-amp through the phototransistor. As I_2 is pulled from the inverting node, the output of the amplifier begins to go high until a current equal in magnitude to I_2 is injected into the inverting node of the amplifier. Since this current, I_2', flows through R2, an output voltage is developed such that:

12. $V_{OUT} = I_2' \cdot R2$

Since $I_2 = I_2'$:

13. $V_{OUT} = I_2 \cdot R2$

The composite equation describing the operation of this circuit is the same as in the photoconductive mode, that is:

14. $V_{OUT} = V_{IN} \cdot K3 \cdot R2/R1$.

Refer to equations 1-10 to understand how equation 14 was solved.

The frequency and phase response for this circuit is shown in **Figure 5**. This circuit has a bandwidth of approximately 40KHz.

Figure 5   Photovoltaic Amplitude Response and Phase Response

Photovoltaic Amplitude Response

Photovoltaic Phase Response

4 Using the LOC210P or LOC211P in a Modem Data Access Arrangement (DAA)

4.1 Background

In the past, the only way to couple signals from the telephone line and provide the isolation necessary has been to use a transformer. With the advent of pocket and PCMCIA (Personal Computer Memory Card International Association) modems, however, the transformer has become a liability in terms of the size, weight and PCB real estate it occupies. Today, PCMCIA modems demand rugged on-board DAA circuits. The LOC eliminates the transformer problem with no performance sacrifice and improved manufacturability and reliability. With Total Harmonic Distortion typically at -87dB and servo non-linearity less than 0.01%, the LOC210P is well suited for high speed modem applications.

4.2 Description

One LOC210P or LOC211P is required for full duplex operation. One half of the LOC is used in the transmit path and the other in the receive path. The photovoltaic mode of operation is usually selected for high speed modem circuits due to the improved linearity and lower noise. **Figure 6** shows a schematic of this DAA. The LOC210P or LOC211P is connected in a similar manner to the circuit shown in **Figure 4**. While there are many ways to design a DAA with the LOC, the figure is intended to be used by the designer as a possible starting point.

4.3 Transmit Path

Referring to **Figure 6**, the TX input of the DAA is AC coupled to the modem's data pump transmit signal via C1. Resistor R5 pre-biases the input amplifier such that a quiescent forward current in the LED is established. The transmit signal from the modem will modulate the LOC LED current above and below this quiescent current. Transistor Q2 provides drive current for the LED. This is required to prevent hard output loading of the op-amp which would increase Total Harmonic Distortion (THD) and increase non-linearity. The output of the amplifier is AC coupled via C8 to the base of Q1. Q1 modulates the loop current on the telephone line in response to the transmit signal thus transmitting the modem's signal over the telephone line.
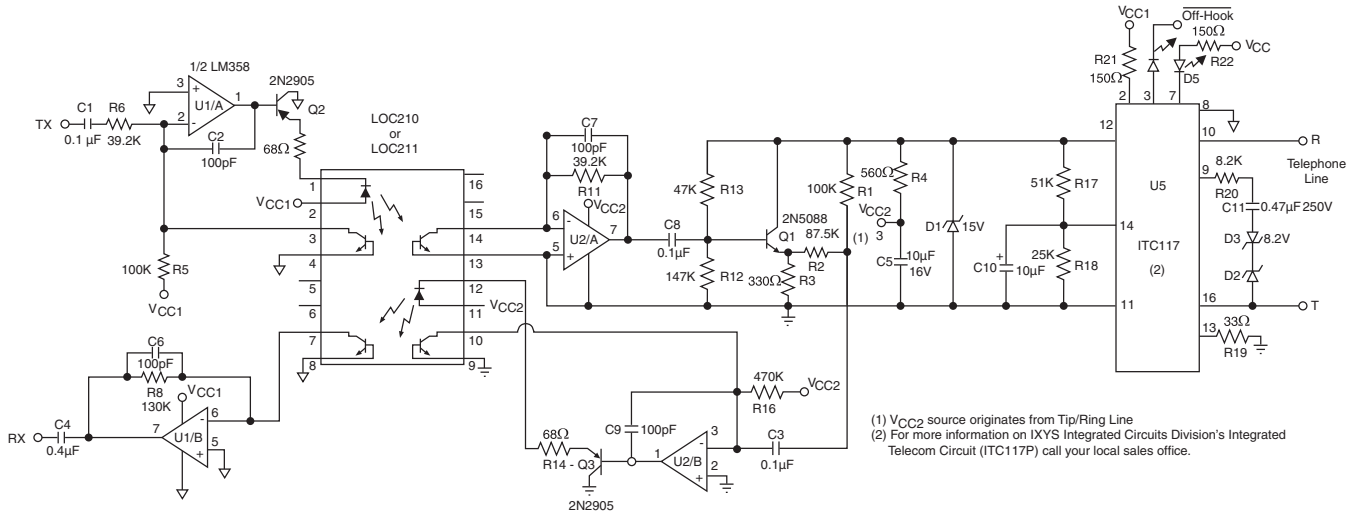
4.4 Receive Path

The receive signal across tip and ring is coupled through R1 and C3 to the input of the isolation amplifier. The receive amplifier drives the LOC LED which takes its power from across the telephone line. The LOC couples this signal which is then AC coupled via C4 and then goes to the receive input of the modem's data pump.

4.5 Echo Cancellation

The transmit signal is removed from the receive path by taking advantage of the inherent signal phase shifts around Q1. The transmit signal on the emitter is 180 degrees out of phase with the transmit signal on the collector. R1 and R2 can be selected such that the transmit signal is essentially canceled out on the node of R1 and R2 while not effecting the receive signal. This cancellation or "trans-hybrid loss" can exceed 30 dB with 1% resistor values and careful matching. It's important to have the modem DAA impedance match the central office impedance which will have the effect of reducing echo. R4 and C5 form an impedance network of 600Ω. Another benefit from R4 and C5 is that it provides V_{CC2} with AC rejection which is used to power the isolating amplifiers on the line side of the circuit.

Figure 6   Typical Modem DAA using the LOC210P

(1) V_{CC2} source originates from Tip/Ring Line
(2) For more information on IXYS Integrated Circuits Division's Integrated Telecom Circuit (ITC117P) call your local sales office.

5   Electronic Inductor

The purpose of the electronic inductor circuit is to sink loop current when the modem goes off-hook thus seizing the phone line. The circuit usually consists of a Darlington transistor, a resistor bias network, and a capacitor to provide AC rejection. This circuit should be designed to work throughout the range of loop currents per FCC Part 68.3. The circuit also presents a high AC impedance to the line so that signal integrity is not compromised. The zener diode is installed for protection of the Darlington transistor and other circuitry on the line side. The zener voltage is selected based on the voltage rating of the other components selected. Refer to **Appendix 1** for details on the electronic inductor design.

6   Switch Mode Power Supply Application (LOC110, LOC111 or LOC112)

Another useful application for the LOC110, LOC111 or LOC112 is in the feedback control loop of isolated switching power supplies. Typically, the DC output voltage of the supply is monitored and fed back to the control input of the switcher through isolated means in order to regulate the output voltage. **Figure 7** shows the most common way of doing this in the past with an additional winding on the isolation transformer.

This winding would generate an AC signal which then needed to be rectified, filtered, and possibly scaled down with a resistor network before going into the control input of the switcher. Using the LOC110, LOC111 or LOC112 to accomplish the same task is a better solution since the special transformer windings, rectification, and filtering are eliminated. Also, the problem of poor load regulation due to inadequate winding coupling is eliminated. Referring to **Figure 8**, the design is almost identical to the basic photoconductive isolated gain amplifier discussed previously, except that the photoconductive mode is used in an isolated unity gain amplifier and a voltage divider consisting of R_A and R_B is added.

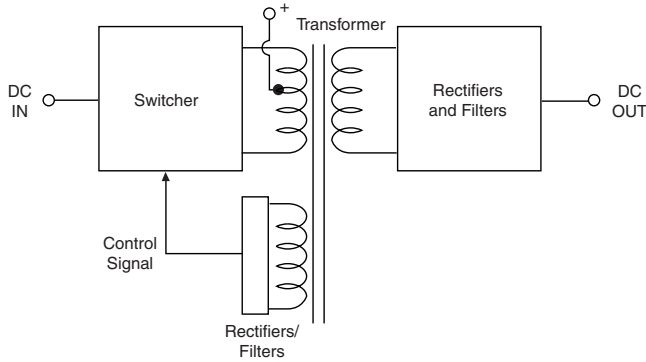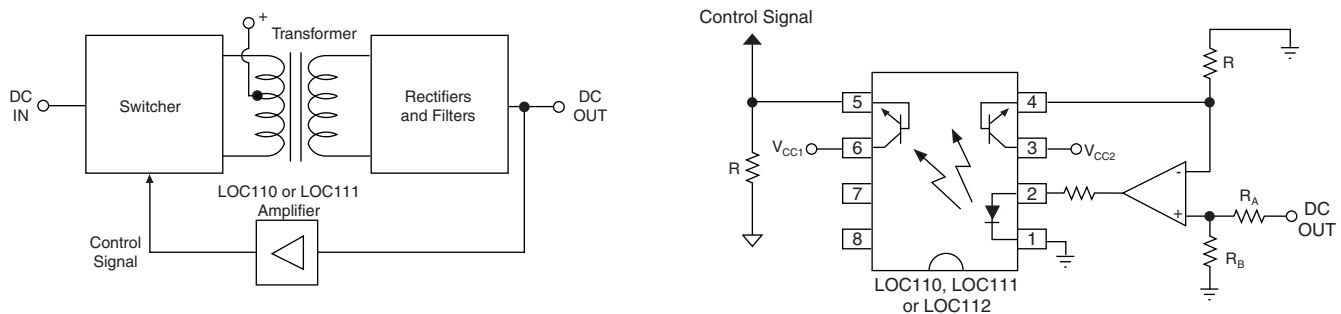**Figure 7   DC to DC Converter with Feedback Wiring**

Figure 8   DC to DC Converter with LOC110, LOC111, or LOC112 Block Diagram and Schematic

7 Cardiac Monitoring Application

Designing equipment to measure Cardiac signals such as the Electrocardiogram (ECG) presents some special problems. Cardiac signals for adults are approximately 1mV in magnitude while for a fetus can be as low as 50μV. Since the heart signals are low in amplitude, noise such as residual electrode voltages and 50/60Hz power line pickup can easily mask the signal. Therefore, it is important to design an isolated amplifier circuit which interfaces to the probe that has high Common Mode Rejection (CMR) ratings to reduce or eliminate common mode noise while providing amplification for the heart signals.

The LOC110, LOC111 or LOC112, with the proper support circuitry, can provide the isolation, amplification, linearity, and high CMRR that is required for this type of application. Referring to the diagram in **Figure 9**, the isolated amplifier block contains the LOC110, LOC111 or LOC112 and high CMRR op-amps. The electrodes are connected to the amplifier via shielded cable to provide noise immunity. The

shield is connected to the patient's right leg for best CMR performance. For good performance, proper shielding, PCB layout and amplifier, design techniques should be practiced.

Figure 9 LOC110 Isolated Amplifier in ECG Application
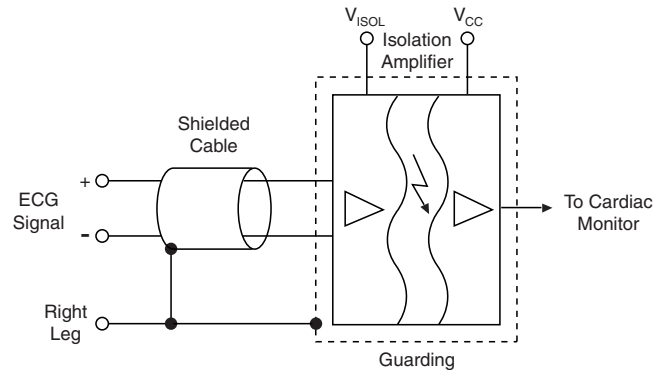
8 Isolated 0-10V to 4-20mA Converter Application

Industrial controllers and data acquisition equipment frequently require an isolated voltage-to-current loop converter in environments where high common mode noise exists and protection of equipment and personnel from high voltages are required. The current loop, usually 4-20mA, is used to drive control valves or the input to chart recorders for temperature/pressure monitoring over time for example. **Figure 10** shows a simplified block diagram of an isolated pressure transmitter.

Figure 10 Isolated Pressure Transmitter
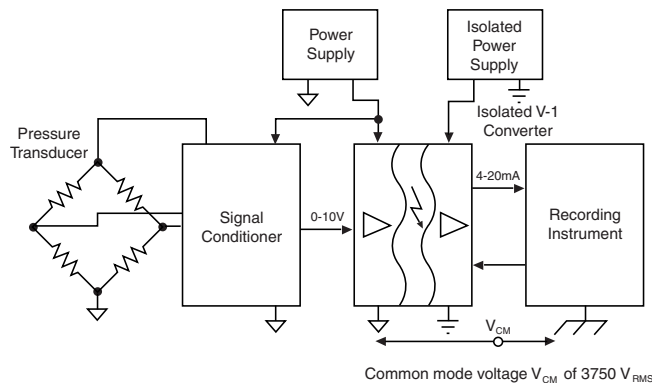
The LOC110, LOC111 or LOC112, with a typical Common Mode Rejection Ratio of 130dB (see **Figure 11**) and isolation voltage up to 3750V$_{rms}$ (E version) is a good choice for this kind of application. The example circuit for this application is shown in **Figure 12**. The LOC110, LOC111 or LOC112 is in the photoconductive mode which has linearity comparable to an 8 bit D/A converter with ±1 LSB nonlinearity or 0.39% of full scale.
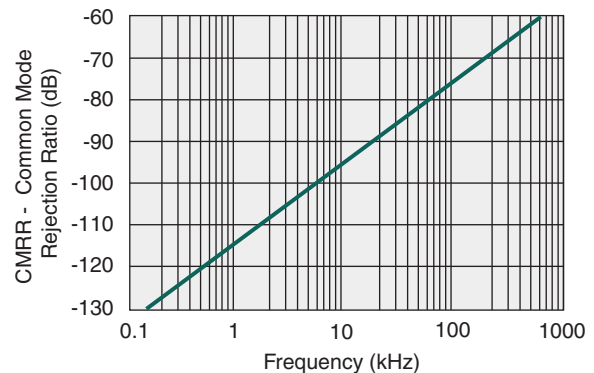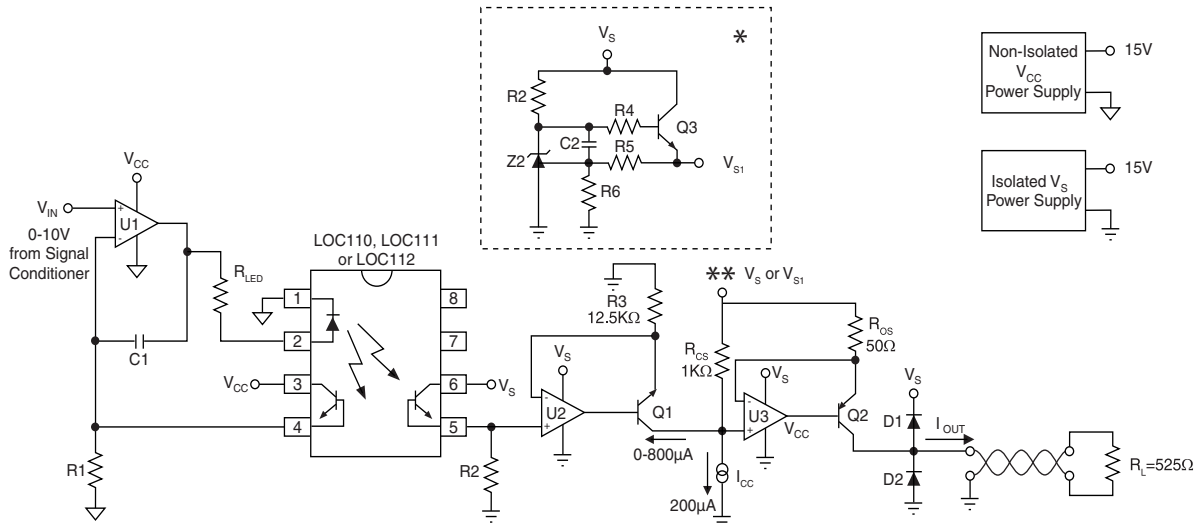
Figure 11 Common Mode Rejection

Figure 12   0V-10V to 4mA-20mA Converter

*   Series regulator: needed if the op-amps used are not Rail-to-Rail (R-R) types

**   Connect only this point to V_s if R-R op-amps are used, otherwise connect point to V_{s1}

For this example, the input to the circuit is 0 - 10V from the output of the pressure transducer signal conditioner. The values of R1 and R2 are calculated based on the K3 of the LOC being used to achieve a 1-to-1 ratio.

Figure 13 V_{IN} vs. I_{OUT}
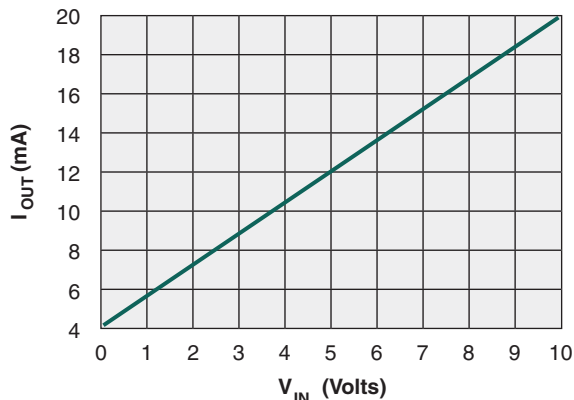
Note that the isolation amplifier portion of the circuit is very similar to the basic photoconductive amplifier discussed earlier. The input will be on a linear scale of 0 - 10V, which equals a 4-20mA output. The circuits will be discussed individually, then brought together to form the system that will achieve the desired results.

The LOC will turn on (t_{ON}) when there is enough voltage and current going through the LED to t_{ON} the

phototransistors. The resistor selection for LED t_{ON} is important. An adequate resistor needs to be chosen to provide the necessary light emission for the phototransistors. A limiting resistor value will be chosen according to the maximum desired I_F . Using the formula for R_{LED}:

$$R_{LED} = V_t / I_{F\_max}$$
$$= 12.1V / 20mA$$
$$= 605\Omega$$

$$V_t = OpAmp_{out\_max} - V_{F\_max}$$
$$V_{F\_max} = 1.4V$$
$$OpAmp_{out\_max} = 13.5V$$

$$V_t = 13.5V - 1.4V$$
$$= 12.1V$$
$$I_{F\_max} = 20mA$$

V_t = total voltage necessary for the LED to turn on.

V_{F_max} = forward voltage drop maximum.

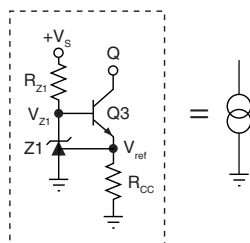I_{F_max} = highest desired forward current through LED.

$OpAmp_{out\_max}$ = maximum output voltage of op amp.

The recommended conditions are being used for operation of the LOC. We are going to use a K1 = K2, which will create a factor of 1 for K3. The resistor values used in the servo for gain will be set equal to each other (R1 = R2), giving a 1-to-1 transfer ratio. By

having the 1-to-1 ratio, the output current of 4-20mA will track with the input voltage of 0-10V.   This converter can also be adjusted for different voltage control schemes, but for this example it will be from 0-10V. Having the control voltage and current output defined, the current source circuit will be designed first. The design will start from the output and finish at the 1-to-1 defined resistor value.

To achieve the desired output currents, Q2 is used to provide the negative feedback to U3. This allows the 4-20mA current output. An adjustable current source was created using U3, Q2, R4, R5, and a constant current source (I_{CC}). A level shifter may be required depending on the op-amp chosen. The current at this point will have to be designed for a 0V input to equate to a 4mA output, and a 10V input to equate to a 20mA output. The variable current circuit will be called an adjustable current source. An additional constant current source will be required, to meet the requirement of a 4mA output with zero volts. A scale factor will have to be determined to meet the specified output. The scale factor chosen will be for every 50µA's drawn from the source, there will be a 1mA output. 50µA is a good value, due to aiding in lower power consumption, which will allow use of smaller, less expensive components, and will produce less heat than higher currents that could be used. The converter will not go below 4mA, which will require a constant current source of 200µA. This value was achieved by multiplying the 50µA by 4, therefore giving 200µA. A 200µA constant current source has to be produced to hold the required minimum output current.

There are many options for constant current sources, but for this example a 3-pin 2.5V zener (Z1), NPN transistor (Q3), and two resistors (R_Z and R_{CC}) will be used. The 3-pin zener, IX431, was chosen since it will provide a feedback network to maintain regulation of the 2.5V from its reference pin. The feedback will connect the cathode of the zener to the base and the reference pin will be connected to the emitter of the NPN transistor. The emitter voltage will be held to 2.5V, so now the constant current resistor (R_{CC}) can be determined.

$$R_{CC} = V_{ref}/I_{CC}$$
$$= 2.5V/200\mu A$$
$$= 12.5k\Omega$$

V_{ref} = Zener Voltage Reference = 2.5V
I_{CC} = Constant Current = 200µA

The feedback network has been determined, and the t_{ON} of the zener has to be met per the datasheet. The minimum regulation current is 400µA, but the recommended minimum operating condition is at 1mA. A 2mA zener t_{ON} current was chosen, to guarantee the device will be on and to provide a minimal base current to the transistor.

$$R_{Z1} = (V_S - V_{Z1})/I_{Z1}$$
$$= (15- 3.2)V/2mA$$
$$= 5900\Omega$$

V_S = Isolated Voltage Supply
V_{ref} = Zener Voltage reference
I_{Z1} = Zener turn-on current
R_{Z1} = Zener turn on resistance
V_{Z1} = Vref + Vbe, (2.5V + 0.7V), Zener Input Voltage

The premise for the current converter working is every 50µA equals 1mA. So, to get a maximum 20mA output, the adjustable current source will have to go up to 1mA, (50µA x 20 = 1mA). The 1mA current can be large with a large voltage drop, creating an extravagant, unnecessary power loss. Due to the current size, and to simplify the conversions, a tenth of a volt change will control the output current.

The bias point for operating the adjustable current source is 0-1V. The op-amp chosen for regulation of the converter is the LM324. This op-amp will require additional circuitry because it is not capable of going rail-to-rail (R-R) and because of the operating conditions under which this design is being done. The datasheet specifies that the output swing of the op-amp is V^+ - 1.5V. The maximum output of the amplifier is +13.5V (for a V^+ = 15V). The goal of this control system is to keep the voltage drop at a minimum with respect to V^+. The reason for the small voltage drop was stated earlier. The op-amp may still be used with the incorporation of a level shift down in V+. Another solution is to use a R-R op-amp. The designer will have to verify the output swing of the op-amp from the manufacturer's datasheet. The LT1366 is R-R capable and, under worst case conditions, the op-amp may produce an output of V^+ - 0.1 (sourcing 5mA) to

V^+ - 0.250 (sourcing 2mA). The sourcing current of the op-amp should not be in the mA range for this application, but to look at worst case scenarios the output could be a maximum of 14.75 to 14.9V. These output voltages are unlikely to be so low, but it is good to know, in the event that a level shift will have to be incorporated, a different op-amp may be selected, or the designer may decide that with the current selection the output produced will suffice. The LT1368 is a good R-R op-amp, but it will not work properly without a $0.1\mu F$ capacitance load at the output. This output capacitance might affect the circuit, and proper modifications might be required. The important thing is to read the datasheet and know the output swing/operation of the op-amp.

For this example, the converter will be demonstrated to work with the LM324. Again looking at the datasheet and picking the worst case, a level shift from V^+=15V down to V^+=13V will be used to allow the op-amp's output to produce 13V. In this manner, everything is shifted downward by 2 volts. The control will now be between 12.0V and 12.8V. The level shift will require a series regulator. For the series regulator an NPN transistor (Q4), a zener (Z2), resistors (R6, R7, R8, R_Z), and a capacitor (C2) will be used.
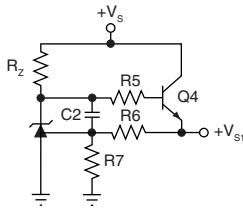
The IX431 2.5V reference will be gained to provide the desired voltage of 13V. R_{Z2} has been selected as was described earlier, except that V_{ref} will be replaced by V_Z. V_Z = 14V, which will be used to provide the regulation for the zener and the transistor.

$R_{Z2} = (V_S - V_{Z2}) / I_Z$
$\quad = (15 - 14)V / 2mA$
$\quad = 500\Omega$

V_S = Isolated Voltage Supply
V_{Z2} = Zener Input Voltage
I_Z = Zener Turn-On Current
R_{Z2} = Zener Turn-On Resistance

The R5 resistor value was chosen to be a small value to help in regulation/feedback of the 13V. The capacitor was added to provide stability for the regulator. The

NPN transistor, 2N3904, is rated for 200mA; for this example, it will use less than 25mA. This transistor will be adequate without using a Darlington configuration with a power transistor. To achieve the 13V, the Zener will have to be gained. The formula for this is:

$V_{OUT} = ((R5/R6) + 1)V_{ref}$
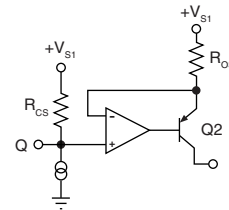$\quad 13V = (R6/2.5k\Omega) + 1)2.5V$

$V_{OUT} = 13V$
$V_{ref} = 2.5V$

R6 was chosen to be $2.5k\Omega$
R5 = $10.5k\Omega$
R4 = 300Ω

With the level shift completed, the ratio of R_{OS} to R_{CS} needs be done. First a low value needs to be chosen. $1k\Omega$ will be chosen and it will be divided by our step value of 20. As discussed, every $50\mu A$ equals a 1mA increase in output. So it will take 20 increments of $50\mu A$ to achieve an out of 20mA. The control current for the 20mA output will be $50\mu A \times 20 = 1mA$. The design can be completed by using ohm's law for the resistance values on the control side (CS) and the output side (OS).

$R_{CS} = V_{CS} / I_{CS}$ $\quad\quad R_{OS} = V_{OS}/I_{OS}$
$\quad = 1V/1mA$ $\quad\quad\quad\quad = 1V/20mA$
$\quad = 1000\Omega$ $\quad\quad\quad\quad\quad = 50\Omega$

The ratio for R_{CS}/R_{OS}
=1000/50
= 20

R_{CS} = Resistor on control side
R_{OS} = Resistor on output side
V_{CS} = Voltage on control side
V_{OS} = Voltage on output side
I_{CS} = Current on control side
I_{OS} = Current on output side

The ratio is consistent with the increment value that was selected for the control current, which should hold true with every $50\mu A$ of input current resulting in 1mA of output current. The control system is based on a 0.2V - 1V drop. This will give a small voltage drop. The

resistor wattage will be chosen for the maximum current and resistor value.

$$P_{CS} = (I_{CS\_max})^2 \times R_{CS} \qquad P_{OS} = (I_{OS\_max})^2 \times R_{OS}$$
$$= (1mA)^2 \times 1k\Omega \qquad\qquad = (20mA)^2 \times 50\Omega$$
$$= 1mW \qquad\qquad\qquad = 20mW$$

Note that the incremental value of 20 still applies.

The power rating for the resistors of 1/16th watt (62.5mW) will provide ample margin for both resistors.

An op-amp with a PNP transistor (Q2) is used to form a unity gain buffer for regulation, and the PNP serves the purpose of allowing the higher current to flow. A low output current amplifier may be used, since it is only providing the base current, which will be small. Also, keep in mind that the lower the output current of the op-amp the higher the Beta of the PNP will need to be to guarantee proper operation. When the current is adjusted from 200μA - 1mA, it will create voltages from 12.0V to 12.8V. When the non-inverted side is 12.0V, the inverted side will also be 12.0V. This produces:

$$I_{OUT} = (V_{S1} - V\text{-})/R_{OS}$$
$$= (13 - 12)V/50\Omega$$
$$= 1V/50\Omega$$
$$= 20mA$$

I_{OUT} = the desired output current ranging from 4mA - 20mA

R_{OS} = resistor on the output side, it is the output current regulating resistor

The output of the amplifier and base of the PNP should be equivalent to 11.3V. This is due in part to the V_{be} of the transistor and to the regulation of the op-amp to maintain a unity gain operation.

It is the same circuit used to control the current with the exception of the NPN transistor (Q1). The NPN is used to draw current from what will create the bias point at Q. By drawing the current through the NPN, point Q's voltage will vary between 12.0V and 12.8V, allowing the 4-20mA current through the PNP transistor.
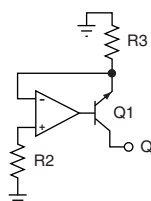
To produce 4 - 20mA, a current needs to be produced varying from 200μA- 1mA. The incorporation of a constant current source providing 200μA, means the NPN will have to draw a maximum of 800μA to give the necessary adjustable current control regulation. The current range that will be passed through the NPN will be 0 - 800μA. Since the LOC was set to have a 1-to-1 transfer ratio, the resistor value (R1=R2) is the same on the isolated/non-isolated side. The control voltage from the input is 0V to 10V. The output of the LOC will produce 0V to 10V. The op-amp with the NPN forms a unity gain amplifier. The value for R3:

$$R3 = V_{Omax}/I_{NPNmax}$$
$$= 10V/800\mu A$$
$$= 12.5k\Omega$$

V_{Omax} = the maximum output voltage produced from the LOC.

I_{NPNmax} = the maximum current that will be drawn through the NPN transistor

R3 = the resistor that will regulate the current drawn.

The LOC is being used in a linear fashion. When the input is 0V, the NPN will draw zero current and the constant current source will be providing the 200μA needed to produce the 4mA output. As the input voltage is varied linearly to 10V, the current moves linearly to 20mA. When the input is 10V, the output of the LOC is 10V, and the NPN is drawing 800μA, plus the 200μA(from the constant current source) making the 1mA current needed for the 20mA output. V_{IN} vs. V_{OUT} is shown in **Figure 13**.

Additional considerations would be to add protection circuitry. A pair of diodes at the output of the PNP transistor will protect the transistor from transients that could occur on the line. This will divert transients above V+ to be dissipated through D1 and for transients below ground to be dissipated through D2. A twisted pair of cables will help with noise immunity, by canceling fields created by connecting to the external load.

Table of Components Used

Component	Description	Part #	Manufacturer
Q1, Q3	NPN	2N3904	Motorola, Fairchild, OnSemi †
Q2	PNP	2N3906	Motorola, Fairchild, OnSemi †
Z1, Z2	Zener	IX431	Micronix †
U1-U3	OpAmp	LM324	National Semiconductor †
		LT1366	Linear Technology †
R1, R2	10kΩ		
R$_{LED}$	605Ω		
R3, R$_{CC}$	12.5kΩ		
R4	300Ω		
R5	10.5kΩ		
R6	2.5kΩ		
R$_{CS}$	1kΩ		
R$_{OS}$	50Ω		
R$_{Z1}$	5.9kΩ		
R$_{Z2}$	500Ω		
C1	100pF		
C2	0.1uF		
D1, D2	Diode	1N4148	
† This is not a complete listing of possible components or manufacturers.			

9   Summary

Here are some guidelines when designing with the LOC:

- Use photoconductive mode for applications where up to 200kHz bandwidth is required and linearity comparable to an 8-bit D/A converter with ±1 LSB (Least Significant Bit) linearity error is acceptable.
- Use photovoltaic mode where up to 40KHz bandwidth is required and linearity comparable to a 13-to-14 bit D/A converter with ±1 LSB linearity error (0.01%) is acceptable.
- Drive LED with a transistor buffer to maintain the best linearity and to keep Total Harmonic Distortion (THD) to a minimum.
- For high resistance values (>30K), it may be necessary to put a 100pF capacitor from the output

of the op-amp to the input as shown in **Figure 1**. This will help prevent oscillations.
- For bipolar operation, select a quiescent LED current. The superimposed AC input signal will swing above and below this current. A quiescent LED current is generated by pre-biasing the op-amps such that in the absence of an AC signal, a current flows through the LED.

The following is a brief list of possible op-amps[†] which may be used in conjunction with the LOC Series:

- LMC6484
- LM358
- LM201
- LM1558

[†] This is not a complete listing of op-amps.

Table 1:   Typical Applications Using the LOC110/LOC210

Industry Segment	Application	Mode	Function
	Modem DAA	PV Mode for best linearity 0.01%	H. V. Isolation, Signal Coupling with 40KHz bandwidth
	PBX Isolated SMPS* for Ring Generator	PC Mode for 200KHz bandwidth, 0.39% linearity	Isolated voltage sensing for SMPS* feedback
Industrial	Industrial RTD (Resistance Temp. Device)	PV or PC depending on desired linearity and bandwidth	High CMRR** for noise immunity, HV isolation, signal coupling
	Isolated Pressure Sensing	PV or PC depending on desired linearity and bandwidth	High CMRR** for noise immunity, HV isolation, signal coupling
	Isolated 4-20mA Converters	PV or PC depending on desired linearity and bandwidth	High CMRR** for noise immunity, HV isolation, signal coupling
Medical	Isolated EGG/ECG Amplifier	PV or PC depending on desired linearity and bandwidth	Couples low-level signals from transducers, HV isolation, noise immunity
Instrumentation	PH Probe	PV Mode	Maintains high CMRR** for remote PH probe, provides amplification and HV isolation

*SMPS: Switch-Mode Power Supply

** CMRR: Common-Mode Rejection Ratio

10 Appendix 1

10.1 Electronic Inductor Design

The electronic inductor approximates the operation of a discrete inductor by using a Darlington transistor, three (3) resistors and a capacitor. When used in a modem application, the electronic inductor will present a relatively low impedance to DC currents and a relatively high impedance to AC signals.

10.2 Circuit Description

Figure 14 shows the electronic inductor in a typical modem environment. Bridge D2 rectifies current on tip and ring for the electronic inductor only. This ensures line-polarity insensitivity required by most regulatory agencies. Diode D1 protects Darlington Q1 from excessive transient voltages when going off-hook. The zener voltage should be less than the V_{CEO} of the Darlington. R1 and R2 set the biasing point for Q1. C1 is used for AC rejection of signals at the base of Q1. C1 should be a good quality Tantalum rated at a minimum of 10WV (working voltage). R3 is used to provide negative feedback for Q1 so that Q1 will not go into saturation over the loop current range. The AC signal path is coupled to the modem's transformer via C2. C2 should have a working voltage of 100V, or 50V if two capacitors are used, one on each lead of the primary.

Figure 14   Dry Circuit with Electronic Inductor
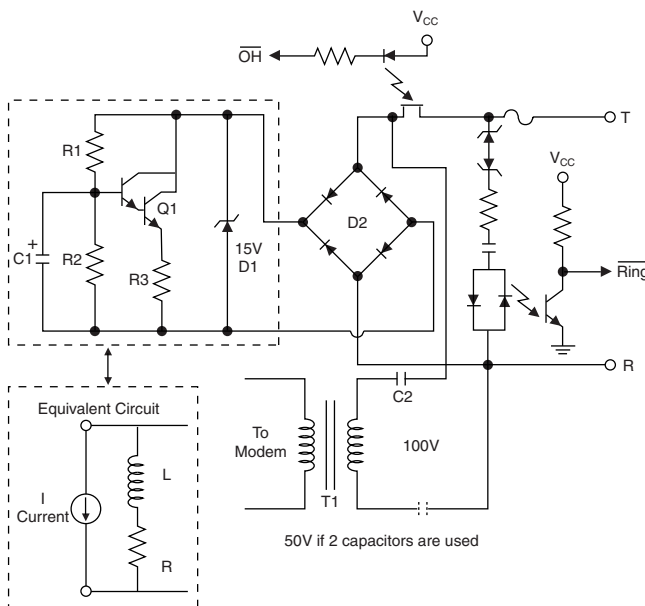
10.3 DC Characteristics (Figure 15)

The electronic inductor should be tailored to meet the following requirements:

- CO (Central Office) Battery (42.5V_{DC} - 56.5V_{DC})
- Loop Resistance (400Ω - 1740Ω)

Maximum allowed DC-resistance of CPE (Customer Premise Equipment) in off-hook mode (200Ω) per FCC 68.314 (c1), (c2).

Minimum recommended DC resistance in off-hook mode (90Ω) per EIA-496A, 4.2.2.1.

The two extremes of operation are as follows:

1. Minimum loop current:
    - CO battery drops to 42.5V_{DC}
    - Loop resistance is 1740Ω
    - Electronic coil has highest DCR of 200Ω resulting in a minimum loop current of 22mA
2. Maximum loop current:
    - CO battery is 56.5V_{DC}
    - Loop DC resistance is 400Ω
    - Electronic coil has the lowest DCR of 90Ω the resulting maximum current is 115mA

The circuit should be tested per FCC 68.314 which consists of a battery and variable resistor to simulate proper operation at the above stated conditions.

Figure 15   Central Office to CPE Interconnect
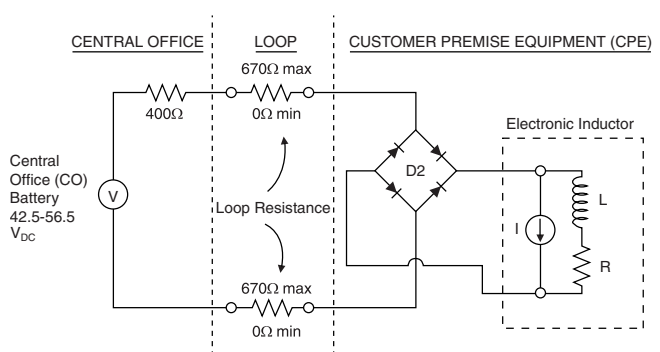
10.4 AC Characteristics

For good performance, the electronic inductor should emulate an inductance of between 4-10H. To approximate the value of the inductor: L = R1 • C1 • R3.

11 Appendix 2

11.1 Photoconductive Description

When the LOC is used in the photoconductive mode, the phototransistors are operated with the collector and base reverse-biased as shown in **Figure 16**. The equivalent circuit model is also shown and illustrates the photocurrent source I, dark current component I_D, intrinsic diode D, and junction capacitance C_P The incident flux from the LED on the phototransistor

causes a photocurrent (I) to flow from the collector to the base and through the load resistor R_L. This photocurrent is linearly proportional to the LED flux. The output voltage V_O results from the product of the photocurrent (I) plus a small dark current times the load resistance R_L: $V_O=[I+I_D] \bullet R_L$. The dark currents from both phototransistors track closely and are canceled when used in the servo mode.

Figure 16   Photoconductive Circuit, Circuit Model, and Photoconductive Responsivity
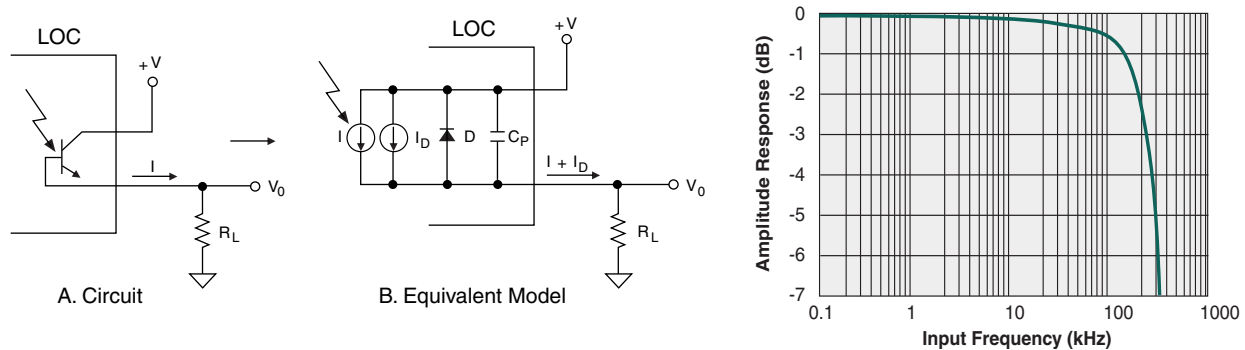
One of the attributes of the photoconductive mode is a bandwidth of about 200KHz. This is considerably higher than the photovoltaic mode bandwidth discussed earlier which was around 40KHz. One of the reasons for this is that with the photoconductive mode, since the base-collector junction is reversed biased, the depletion area of the junction is wider than when no bias or forward bias is applied. The wider depletion area of the junction results in a lower junction capacitance (C_P in **Figure 16**) which results in a faster rise time or responsivity:

$t_R=R_L \bullet C_P$

As the magnitude of the reverse bias is increased, the depletion width of the junction gets wider resulting in lower junction capacitance C_P .

The responsivity of the phototransistor in this mode is shown in **Figure 16**. Note that the responsivity decreases only 3% from a +V of 15V to 5V.

11.2 Photovoltaic Description

When the LOC is used in the photovoltaic mode the phototransistors are operated with the collector and

base forward biased. **Figure 17** shows a typical circuit with a simplified model. In this mode the phototransistor has no external power source available to it like in the photoconductive mode where there was a +V source at the collector. Instead, the phototransistor delivers power to an external load, R_L, in response to the LED emission. Since there is no external power source connected to the phototransistor there is no dark current.

Referring to **Figure 17**, as the current I increases with an increase in incident LED flux, a voltage is developed across R_L.

Figure 17   Photovoltaic Model
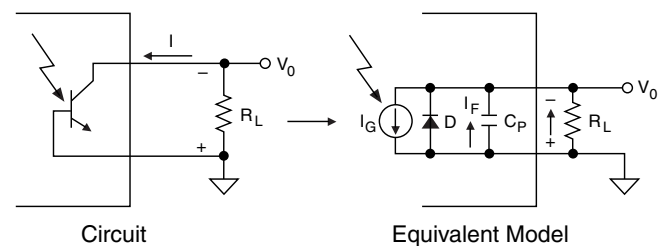
This voltage however becomes increasingly nonlinear as more current (I_F) begins to flow through the intrinsic diode D or as R_L is increased in value. This can be illustrated by looking at a simplified equation of the current flow through the junction. The total current consists of two parts, one part is the current that flows through the intrinsic diode I_F the other is the photogenerated current from the LED flux I_G:

$$I_{total} = I_F - I_G$$

I_F can be expressed with the diode equation:

$$I_F = [I_S(e^{\frac{V_O}{K}} - 1) - I_G]$$

I_S is the source current.

The total current can be expressed as:

$$I_F = I_S(e^{\frac{V_O}{K}} - 1)$$

As R_L approaches 0Ω the output voltage V_O approaches 0V, at which time the diode term for the current equation drops out and the total current is equal in magnitude to the photogenerated current I_G which is linearly proportional to the incident LED flux:

$$I_{total} = I_G \text{ with } R_L = 0\Omega$$

The equivalent circuit is shown in **Figure 18** with $R_L = 0\Omega$.

Figure 18   Equivalent Circuit with $R_L = 0\Omega$
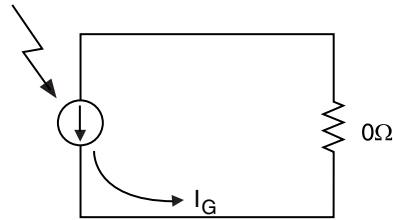
To achieve 0V bias, the configuration shown in **Figure 19** is implemented. The inverting input of the amplifier is at virtual ground so a 0V bias is obtained. When LED flux is incident on the phototransistor, a current is generated by the phototransistor and pulled from the inverting input. Since, by Kirchoff's law, the sum of the currents entering and leaving a node must be zero, the amplifier responds with a current I_1 of equal magnitude to the current leaving the node I_G, and is injected into the inverting node via R_F which maintains zero volts at this node. The output voltage of the op-amp is the current $I_1 \bullet R_F$.

Figure 19   Implementation of 0V Bias in Photovoltaic Mode

Circuit   Equivalent Model
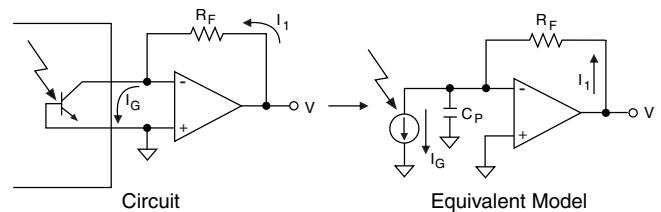
The junction capacitance is higher than in the photoconductive configuration due to a zero volt bias which results in a narrower depletion region and a higher junction capacitance which limits the bandwidth to approximately 40KHz.

For additional information please visit our website at: www.ixysic.com