

RATIOMETRIC COMPENSATED OPTICAL ISOLATION COUPLER

Background of the Invention

This invention relates to opto-couplers and opto-transformers and more particularly relates to opto-couplers having a gain associated with the optical coupler.

Description of the Prior Art

5 With the development of small form factor modems and line terminals for use particularly in association with notebook and subnotebook computers and personal digital assistants (PDA's), it has become necessary to miniaturize telephone line couplers. Traditionally, for example, in modems, the coupling circuitry to the telephone line to provide line isolation comprised isolation transformers. With the development of PCMCIA form
10 factor modems and ISDN terminals, use of such transformers became impractical as the transformers are too large for the form factor. As a substitute, opto-electrical isolation circuits or so called optical isolation transformers were developed. Optical isolation transformers typically comprise one light emitting diode or other light emitting device optically coupled to a photosensor such as a photodiode or phototransistor preferably
15 contained in a single IC package. On the transmit side of the device, the modulator or circuitry is coupled to the light emitting diode and the telephone line or hybrid circuitry is coupled to the phototransistor or diode. Conversely on the receive side of the device, the interface circuitry is coupled to the light emitting diode and the photodiode or transistor is coupled to the modem circuitry. The opto-transformer comprises both the transmit and
20 receive opto-couplers and associated circuitry.

 A problem with conventional opto-couplers such as those described above is that they have a gain associated with them. This gain or scaling varies between couplers and also varies with temperature and aging along with other factors. To compensate for such varying gain compensation, one common technique is to use a feedback network 2 as shown in
25 Figure 1. In such feedback techniques, each opto-coupler includes one light emitting diode and two light sensitive elements such as two photodiodes or phototransistors for providing the necessary coupling for each half of the duplex channels needed for the opto-transformer. One of the photodiodes or transistors 2 is coupled to the modem or the telephone line as shown in Figure 1 and the other is coupled to the same circuitry 4 as the light emitting diode.
30 The second photosensitive element in each of these circuits is used for providing feedback to permit compensation for the gain. Since both photosensitive elements are formed on the

same die, the gain of both will be the same (or at a predictable ratio to each other). Therefore, by using the second photosensitive element in a feedback circuit with the photodiode 4, gain compensation can be provided.

However, use of such gain compensation techniques has several drawbacks. First, the requirement of the additional element for feedback along with external components for frequency compensation to control the current through the light emitting element increases cost and the space required for the opto-transformer on a printed circuit board. Also, such feedback capable opto-couplers have two extra pins for each additional sensor of the opto-couplers so that the total number of signal pins is typically six. While in conventional circuit boards this may not be a disadvantage, on small form factor devices such as PCMCIA devices, this increased use of space is highly undesirable. In addition, use of such feedback techniques raises noise problems for higher frequency telephony circuits and networks frequency compensation problems. For example, using XDSL lines operating at speeds of greater than 1 MHz, several external capacitors and inductors may be needed to keep the circuit stable. In addition, the phototransistors have a large Miller capacitance that may cause problems with high frequency operation. Also, external components increase noise problems and require additional space on small form factor circuits. Still further, such circuits are prone to having varying response to temperature.

Therefore, it is a first object of the invention to provide gain compensation of an opto-coupler without a second photosensor for a feedback circuit. It is a second object of the invention to provide such frequency compensation without increasing the amount of space required on the printed circuit board to permit use of a gain compensated opto-coupler transformer in small form factors. It is a third object to reduce the number of components and therefore the cost. It is yet a fourth object of the invention to provide such opto-isolation without requiring additional components and use conventional technologies. It is yet an additional object of the invention to provide such opto-isolation with feedforward compensation. It is yet a fifth object to provide such opto-isolation with a broad bandwidth and it is yet a sixth object to provide such opto-isolation with extra low voltage power supplies.

30 Summary of the Invention

These and other objects are achieved by embodiments of the invention using an opto-coupler comprising a light source optically coupled to a photosensor along with a half bridge embodiment to provide ratiometric compensation for the gain of an opto-isolator controllable

conductance. In particular, a light emitting diode is supplied with a known reference current and the effective conductance of the detector circuit is leveled with respect to a fixed bias voltage. The known current bias is fed forward to the detector transistor or diode and is referenced to the bias voltage.

5 In a low frequency embodiment such as is suitable for conventional modems, a passive half bridge embodiment may be used. A fixed reference DC current is provided to the light emitting diode. A phototransistor is optically coupled to receive the light from the light emitting diode and is coupled at a node in series between the power supply voltage and ground in series with a variable conductance element such as a FET. The half bridge circuit
10 also comprises a voltage divider providing a reference voltage for the fixed bias voltage. An integrator having a low cut off frequency maintains the DC voltage at the node equal to the DC voltage provided by the voltage divider by controlling the conductance of the variable conductance element. This ratiometrically neutralizes the current transfer ratio of the opto-coupler.

15 As an alternative for higher frequency circuits such as XDSL, an active half bridge circuit is used with the Miller capacitance of the opto-detector effectively removed from the detector side. The DC and AC voltage at the node between a FET and the photosensor is held constant to provide ratiometric control with a first op amp using a controlled resistive feedback to hold both the AC and DC components of the voltage at the node constant. In a
20 third embodiment for low voltage applications, the output of the phototransistor is coupled through a current mirror to the controlled resistance.

Description of the Figures

FIGURE 1 is a diagram of a prior art opto-electrical transformer as is commonly used in telephony circuits such as modems.

25 FIGURE 2 is a diagram of a first embodiment of the invention for use at frequencies of less than about 20 KHz.

FIGURE 3 is a diagram of a second embodiment of the invention for use at higher frequencies.

30 FIGURE 4 is a diagram of a third embodiment of the invention for use in low voltage applications.

DETAILED DESCRIPTION OF THE INVENTION

FIGURE 2 is a schematic diagram of a first embodiment 100 of the invention. An opto-coupler 102 comprised of a light emitting diode 104 and a phototransistor 106 is used for each half of a duplex channel. The light emitting diode 104 is coupled as part of the primary side 110 of the transformer to a varying current source (not shown) such as the telephone line, the hybrid circuit coupled to the telephone line, or the modulator of a modem. Coupled in series with the voltage source is a fixed current source 114 that provides a known bias current I_1 . The fixed bias current I_1 is added to the AC current i_s from either the modulator or the telephone line and the combined currents flow through the light emitting diode 104 causing the light emitting diode 104 to emit light. For small signal currents i_s relative to I_1 , modulation of the light emitting diode output is proportional to the modulating current i_s .

The secondary part 120 of half of the opto-transformer is coupled to the telephone line or the hybrid circuit of the telephone line or the demodulator of the telephone line (not shown). The secondary 120 comprises a phototransistor 106 that is optically coupled by light so that the collector current is the phototransistor current $(I_1 + i_s)$ scaled by a current transfer ratio K . The collector of the phototransistor 106 is coupled in series at an output node 126 to a controllable transconductance element 122, which may for example be a field effect transistor operating as a voltage controlled resistor. The transconductance element 122 is preferably coupled to a fixed reference voltage such as V_{CC} . A fixed DC bias V_B is also provided such as $\frac{1}{2}V_{CC}$ by a voltage divider 121 coupled between V_{CC} and ground. Alternatively, other reference voltage generators such as a temperature compensated band gap generator may be used. Completing the half bridge circuit comprising half of the secondary 120 of the duplex channel opto-transformer is a control element 128, which may preferably be an integrator having an arbitrarily low cutoff frequency such as less than ten hertz (or below the minimum signal frequency of interest). The inverting input of the control element 128 is coupled to the node 126 and the non-inverting input is coupled to the reference voltage V_B .

Looking at the DC operation of the circuit 100, the current flowing through the primary side is I_1 so that the DC current through the phototransistor is KI_1 . The control element 128, which only has a DC gain, controls the conductance of the controllable transconductance element 122 so that the DC voltage at node 126 remains constant. Since the DC bias is a constant across the phototransistor 106, the equivalent resistance of the phototransistor R_{EQ} will be:

$$R_{EQ} = \frac{V_B}{K \cdot I_1}$$

Since the AC current through the phototransistor equals $K \cdot i_s$, the AC voltage across the phototransistor V_{AC} will be equal to $K \cdot i_s \cdot R_{eq}$. By substitution, the ratiometric compensation becomes apparent as the variable K drops out with the AC voltage component across the phototransistor being as follows:

$$V_{ac} = I_s \cdot V_B // 1$$

5 Hence, the output AC voltage at node 126 may be provided through a buffer or other isolation circuitry for further processing by the demodulator portion of the modem (not shown) or for transmission over the telephone line. This output voltage is independent of the current gain of the optical isolator as K is not a term in the AC voltage. Further, because of ratiometric compensation (i.e. $V_B = \frac{1}{2} V_{CC}$), when the voltage divider is used to generate V_B ,
 10 this allows V_{CC} to change without a gain effect. The output voltage can be taken at node 126 through a buffer amplifier or the like.

In an alternative analysis, the opto-transformer has a fixed transconductance of V_B/I_1 since V_B and I_1 are constants. Further, the ratiometric compensation is attained by providing a fixed reference current to the emitter diode and by leveling the conductance of the detector
 15 with respect to a fixed bias voltage V_B . The current bias I_1 at the emitter diode is forward referenced to the bias voltage V_B on the detector transistor, thereby providing feedforward compensation.

However a drawback of the circuit of FIGURE 2 is that the frequency response characteristics of the circuit are limited by the Miller capacitance of the phototransistor 106.
 20 Therefore, the embodiment of Figure 2 is limited to signals having a frequency cutoff of about twenty kilohertz such as in V.34 modems.

FIGURE 3 shows a second embodiment 200 of the invention for high frequency operation such as in ISDN modems or terminals or XDSL (ADSL or HDSL) modems with like components bearing like numbers as those used in FIGURE 2. An optical isolator 202
 25 comprised of a light emitting diode 204 and a phototransistor 206 is used for each half of a duplex channel. The light emitting diode 204 is coupled as part of the primary 210 to a varying source such as the telephone line (not shown) or the modulating circuitry of a terminal or modem to produce a variable current i_s . Coupled in series with the variable

current is a fixed current source 214 that provides a fixed bias current I_1 .

The half of a secondary side 220 of the duplex channel opto-transformer comprises a phototransistor 206 that is optically coupled by light so that the collector current is the light emitting diode current scaled by a current transfer ratio K . The collector of the phototransistor 206 is coupled to a drain of JFET 233 and the inverting input of an operational amplifier 235. The output of the amplifier 235 is coupled to the source of the JFET 233 and to a resistor R_1 . In operation, the JFET 233 acts like a voltage controlled resistor so that the op amp 235 will force the voltage at the inverting input to be equal to V_B , a reference voltage applied to the non-inverting input of the amp 235. The resistor R_1 is also coupled to the inverting input of the amplifier 237 and the output of amplifier 237 is coupled to the gate of the JFET 233. Amplifier 237 is configured as an integrator or other type of low pass filter and preferably has a cutoff frequency of about ten hertz. Hence amplifier 237 will force the DC voltage at the output of the amplifier 235 to be V_δ . The two fixed reference voltages V_B and V_δ are provided by a voltage divider (not shown) permitting V_{CC} to vary without a gain effect or other reference source such as a bandgap voltage generator with a voltage multiplier to generate both V_δ and V_B . The two reference voltages are preferably constrained by the following formula:

$$V_\delta \approx 2V_B$$

The first operational amplifier takes the difference between the output of the photodetector 235 and the bias V_B to provide an AC voltage portion proportional to the AC (K_i) current through the phototransistor 206. The FET 233 is controlled by the second operational amplifier 237 to impose a DC bias of V_δ on the output of the first amplifier 233. Since the FET is controlled by the integrator that substantially attenuates the effects of the AC signal components, the DC component added by the FET 233 to the output of the first amplifier keeps that output at substantially equal to V_δ . Further, the DC voltage across the phototransistor is constrained to be equal to V_B as is the voltage drop across the FET 233. As a result, the same ratiometric control as explained above is achieved using two fixed bias voltages in the secondary stage and a fixed bias current in the primary stage.

In addition, the circuit of FIGURE 3 has a much wider bandwidth than typical opto-isolation circuits. In the circuit of FIGURE 2, at high frequency, the Miller capacitance of the phototransistor 106 degrades high frequency performance, and typically limits bandwidth to twenty kilohertz. However, op amp 235 in the AC domain is configured as a

transresistance amplifier and strives to hold node 236 to be equal to V_B . As a result, although a variable current (Ki_s) passes through the phototransistor 206, the Miller capacitance has no effect (within the open loop gain limits of the amplifier 235). Hence, the output of the op amp 235 can be used as the circuit output, effectively increasing bandwidth to the limit of the junction capacitance of the light emitting diode 204. Thus the overall bandwidth of the opto-transformer is on the order of several megahertz.

It should be noted that the embodiment of Figure 3, while described with a JFET 233 could also be done with a P- or N-channel MOSFET or JFET. In that event, the coupling to the inverting and the noninverting inputs of the second operational amplifier 237 need to be switched and a small RC network needs to be added in between the output of the second operational amplifier and the control node of the P-channel FET such that the signal voltage is divided by two at the gate.

As still a third embodiment 300, particularly for use in low voltage applications is shown in Figure 4 that also has a broad bandwidth. In the embodiment of Figure 4, each half of the primary 310 for a duplex channel has a different configuration than in the other embodiments. A voltage drive V_{IN} from the input such as a telephone line or the transmitter drives a series resistor 301 and capacitor 303 forming a high pass filter. A current source provides a constant bias current I_1 and is in parallel with the light emitting diode 304 of the opto-coupler 302. The light emitting diode 304 is optically coupled by a gain scaling factor K to the phototransistor 306 of the optical transformer 302 providing a current at the collector equal to $K(I_1+i_v)$, where i_v is the current through the light emitting diode 304 in response to the voltage at the input V_{IN} .

The induced current $K(I_1+i_v)$ flowing through the collector of phototransistor 306 is coupled from an input of a current mirror 350 to provide an output current I_{OUT} proportional to the phototransistor collector current $K(I_1+i_v)$. Emitter resistors RE1 and RE2 set the current ratio of the output current to the collector based upon the emitter resistances and the transistor dimensions in the current mirror 350. The output current develops a voltage (V_{OUT}) across a voltage controlled resistance 351 and that voltage is compared by an integrator 356 with a reference voltage (here 0.62 volts) developed by a voltage divider 352 from a low voltage source 354 (here 3.6 volts) to permit V_{CC} to vary without a gain effect. That comparison is integrated by an integrator 356 having a low cutoff frequency of about 10 Hz to control the resistance of the JFET 351. Also the AC current is provided to the gate of the JFET 351 to linearize the operation of the JFET with a capacitor providing DC isolation. The output voltage V_{OUT} may be coupled to a phone line or receiver through appropriate

buffering.

The embodiment of FIGURE 4 permits operation at extremely low voltage. As long as the saturation voltage of transistor 306 is more than V_{CC} minus a V_{BE} plus the voltage drop across RE1, the circuit will be operational. The two emitter resistances RE1 and RE2 in the current mirror can be used for controlling the currents so that the photo transistor 306 is nominally operating at the center of its operational range and for obtaining the particular desired resistance of the PFET. Further, although the bandwidth of the circuit is not as good as the embodiment of Figure 2, the circuit has a broad bandwidth as the current mirrors strive to hold the voltage at the collector of the photo transistor 306 constant. Further, the circuit still provides the same ratio-less transfer of signal by controlling the equivalent resistance of the photo-transistor in the manner described above by adjusting the resistance of the FET with respect to a reference voltage using a low frequency control loop such as integrator 356.

To form an opto-transformer, two circuits 300 such as those in FIGURE 4 are used. The input of a first such circuit 300 and the output of another such circuit 300 is coupled to a phone line through appropriate buffering circuitry and the hybrid. The output of the first of such circuit 300 is coupled through the appropriate buffering circuit to the receiver or demodulator of the modem and the input of the other of such circuits 300 is coupled to the output of the transmitter or modulator. This combination provides a full duplex opto-transformer but requires four fewer pins than the prior art circuitry and fewer external components than the prior art circuit of FIGURE 1.

Still other embodiments of the circuit would be readily apparent to those of skill in the field. Of course, the use of the opto-transformer need not be limited to telephony applications but could be used in other applications. For example, the primary side 310 of Figure 4 could be used as the primary side in any of the embodiments of Figure 1 and Figure 2. In addition, the ratiometric compensation could be used in other types of isolation couplers where the same or similar problems are encountered. Still further, the entire optotransformer or preferably pairs of the optotransformers could be incorporated in an integrated circuit with the only external components being the capacitors of the integrators. Alternatively, all of the circuitry other than the opto-couplers could be fabricated on one integrated circuit with the opto-couplers on separate integrated circuits to provide better isolation. Therefore, recourse as to the scope of the invention should be had with the claims.

I claim:

1. A opto-isolator circuit isolating a source providing a variable signal at an output with DC isolation in response to a variable input signal comprising:
a primary side including:
5 a light emitting source emitting light in response to a signal applied to the source; and
a fixed bias generator generating a fixed bias signal to be added to the input signal for application to the light emitting source;
a secondary side including:
10 a photodetector having at least two ports and responsive to the light emitting source providing at a port a signal to the light source related to the bias signal plus the input signal by a scaling factor, the magnitude of the scaling factor being unknown;
a reference voltage generator providing a reference voltage; and
15 control circuitry responsive to the reference voltage to ratiometrically compensate for the scaling factor such that the variable signal at the output is independent of the scaling factor.
2. The circuit of claim 1, wherein the control circuitry includes:
a difference circuit responsive to a DC voltage across the photodetector and the reference voltage to produce an output proportional to the difference between the DC voltage and the reference voltage; and
5 a controllable conductance having a first terminal responsive to the sensor and a second terminal controlling the conductance responsive to the output of the difference circuit.
3. The circuit of claim 2, wherein the difference circuit has a cutoff frequency of less than about one hundred hertz.
4. The circuit of claim 2, wherein the difference circuit has a cutoff frequency of less than about ten hertz.
5. The circuit of claim 4, wherein the transconductance has a third terminal, the third terminal being held at a reference level greater than the reference voltage.



6. The circuit of claim 1, wherein the primary side is coupled to one of a group consisting of the telephone line and a transmitter and the secondary side is coupled to a group consisting of one telephone line and a receiver
7. The circuit of claim 5, wherein the light emitting component comprises a light emitting diode and the photodetector comprises a phototransistor.
8. The circuit of claim 1, wherein the control circuitry includes an integrator responsive to the photodetector.
9. The circuit of claim 8, wherein the integrator has a cutoff frequency of less than about ten hertz.
10. The circuit of claim 1, wherein the photodetector operates in the current mode.
11. The circuit of claim 1, wherein a first port of the detector has a DC level and the control circuitry:
 - a first circuit having an input coupled to the first port of the photodetector and a first circuit output, the first circuit output being proportional to twice the DC level plus an AC component proportional to the variable input signal; and
 - 5 a second circuit coupled in feedback with the first circuit to control the DC voltage across the first circuit.
12. The circuit of claim 11, wherein the first circuit comprises an operational amplifier having inverting and noninverting inputs along with an output and a FET coupled between the inverting input and the output and the FET having a control electrode.
13. The circuit of claim 12, wherein the second circuit comprises a low pass filter responsive to the output of the operational amplifier and the control electrode of the FET being responsive to the filter.
14. The circuit of claim 11, wherein the photodetector has an output voltage swing and the first and second circuits have a gain that substantially cancels the output voltage swing of the photodetector, thereby increasing a frequency bandwidth over which the opto-isolator circuit may be used.



15. The circuit of claim 11, wherein the circuit includes a reference voltage generator providing two reference voltages, the first of the reference voltages being approximately equal to half of the second reference voltage, the first reference voltage being approximately equal to the DC voltage generated across the photodetector, and wherein:
- 5 the first circuit includes a first difference circuit to determine the difference between the first reference voltage and the output of the photodetector; and the second circuit includes a second difference circuit to provide at the output of the second circuit a signal proportional between the DC difference
- 10 between the output of the first circuit and the second reference voltage.
16. The circuit of claim 15, wherein the first circuit includes a transistor coupled between the input and the output of the first circuit such that the FET adds a DC voltage approximately equal to the second voltage to the output of the first difference circuit.
17. The circuit of claim 16, wherein the second circuit comprises an integrator having a cutoff frequency of about ten hertz.
18. The circuit of claim 1, wherein the control circuit further comprises:
- a current mirror having a mirror current input responsive to the output of the photo detector and providing a mirror current output a mirror of the signal provided by the detector;
- 5 a controllable resistance coupled to the mirror current output;
- an integrator responsive to the reference voltage and voltage generated across the controllable resistance to provide the radiometric compensation.
19. The circuit of claim 18, wherein the current mirror further includes emitter resistances for adjusting a ratio of the current at the input and the output of the current mirror.
20. The circuit of claim 18, wherein the integrator compares a voltage at the output of the current mirror with a fixed reference voltage.



21. The circuit of claim 1, wherein the primary side further comprises an input signal in series with the light emitting source and the bias generator, the bias generator comprising a current source.
22. The circuit of claim 1, wherein the primary side comprises a voltage input coupled in series with a parallel circuit comprised of the bias generator and the photo detector.
23. A method for providing DC isolation between an input signal having an AC component supplied at an input port and an output signal at an output port having at least an AC component supplied at the output port by using an optical coupler comprising a light emitting device primary stage and a photodetector secondary stage optically coupled to the light emitting device with an unknown scaling factor, the method comprising:
- 5 providing a fixed bias signal to a light emitting device to provide a constant bias to the photodetector; and
- controlling the conductance of the photodetector with respect to a fixed bias
- 10 voltage, wherein the AC component of the signal at the output port varies with the input signal and is substantially independent of the scaling factor.
24. The method of claim 23, wherein the controlling of the conductance comprises forcing a fixed DC voltage across the photodetector.
25. The method of claim 24, wherein the forcing of the DC voltage comprises determining the difference between the DC voltage across the photodetector and a fixed voltage.
26. The method of claim 25, wherein the difference controls the conductance of a variable impedance device such that the DC voltage across the photodetector is fixed.
27. The method of claim 23, wherein the method comprises:
- adding a DC voltage to the voltage across the photodetector to create a summed voltage at a summed node determining the DC voltage difference between the summed voltage and a fixed reference voltage; and



- 5 controlling the DC voltage to be added to the voltage across the photo detector.
28. The method of claim 23, wherein the photo detector produces an output current, the method further including:
 mirroring the current from the photo detector;
 providing the mirrored current to a controllable resistance; and
5 controlling the resistance of the controllable resistance such that the output is substantially independent of the scaling factor.
29. The method of claim 28, wherein the method of controlling the controllable resistance includes comparing a voltage developed across the controllable resistance with a preset voltage and integrating the comparison to set the resistance of the controllable resistance.
30. A circuit for compensating for an unknown scaling factor between the coupling of an input energy emitting component responsive to a current and a sensor responsive to the energy emitting component, the circuit comprising:
 a fixed bias signal generator inducing a fixed bias signal through the energy
5 emitting component; and
 a circuit coupled to the sensor fixing the equivalent resistance of the sensor is fixed in response to the fixed current.
31. The circuit of claim 30, wherein the equivalent resistance is fixed by fixing one of a group consisting of the (1) DC voltage and (2) the AC plus the DC voltage.
32. The circuit of claim 30, wherein the equivalent resistance depends on the scaling factor and the current through the equivalent resistance depends on the scaling factor.

