Versatile Linear and Digital Optocouplers to Reduce Noise and Ground Loop Errors in Measurements

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ABSTRACT

The paper describes design details of low-cost, versatile, linear as well as digital optocoupler circuits used to reduce noise and ground loop errors in measurements. A detailed description of a linear optocoupler circuit for providing galvanic isolation between photodiode signal conditioner ground and the data logger ground is given. We also report use of two single-channel high-speed digital optocouplers to communicate through RS232 protocol isolating the ground of the devices in the detection region of the Cs fountain frequency standard being developed at NPL India. These isolators are versatile, affordable, and give very good results.

Keywords:
Galvanic isolation, Ground loops, Optocoupler.

1. INTRODUCTION

Many electrical and communications networks often have nodes with different ground domains. The potential difference between these grounds can be variable or a constant offset, and can contain various noise components. Ground loop is a common wiring condition where a ground current may take more than one path to return to the grounding electrode at the service panel. Ground loop currents can degrade data signals, produce excessive Electro Magnetic Interference (EMI), and damage components. Galvanic isolation between circuits or nodes in different ground domains eliminates these problems, seamlessly passing signal information while isolating ground potential differences and common-mode transients. In this paper, we describe the occurrence of such ground loops at two places in the Cs fountain experiment and suggest versatile designs of linear and digital opto-isolation circuits as solutions.

Atomic fountain frequency standards provide precise and accurate measurement of time and frequency [1-3]. NPL India is also developing one such Cs atomic fountain [3]. The development of fountain involves plenty of customized electronics and accurate measurement of many physical phenomena such as temperature, humidity, laser power, etc. The accuracy of the results is very much dependent upon measurement of accuracy of these parameters. There are instances when transducer signal conditioner circuit is required to be interfaced with a remotely placed measurement instrument. In such situations, their grounds being not at the same potential, the ground loop voltage makes the signal noisy and unreadable. The situation becomes worse when the signal is very weak. Hence, a proper ground configuration is essential for a good data acquisition system. In section 2 of this paper, design and results of opto-isolation circuits using low-cost, versatile, linear optocoupler IC IL300 are described.

In section 3, the ground loop problem in case of the detection of the return signal of the atomic fountain is addressed. In the detection region of atomic fountain, we need to take care of grounding problem very cautiously because there is a continuous communication between the detection unit and the PC to run the fountain sequence. Due to common ground of PC and detection unit, the transmitted and received bit streams were observed to be affected by induced 50 Hz noise. The noisy data were giving erroneous results. To get rid of this problem, we developed a ground isolator [4] circuit which could easily handle such problems and perform error-free communication. In our design, we use two single-channel high-speed digital optocouplers to communicate through RS232 protocol isolating the ground of the devices.

2. GROUND LOOPS AND LINEAR OPTOCOUPLERS

During interfacing photodiode signal conditioner circuit to one of the channels of a 16-channel data logger system placed on a 19″ rack with a wire length of about 5 m, it was observed that the readings displayed in the data logger were unstable and noisy. The setup is shown in Figure 1. As shown in the setup, grounds of both the circuits are floating and twisted wires are used to reduce the noise. The output of signal conditioner circuit varies from 0 to +1 V depending upon the intensity of the laser beam falling on photodiode and its alignment with the beam. The noise in the measured voltage which was observed in the data logger LCD was due to floating grounds connected with a long length of the cable and low signal to noise ratio due to low signal level (Vo = 0–1 V) of the photodiode amplifier.

To solve this problem, we introduced galvanic isolation between the two circuits by using Vishay Semiconductors' linear optocoupler IL300. The commercially available isolators, viz. transformer-coupled isolation amplifiers 3656 (Burr Brown) and optically coupled linear isolation amplifiers 3650, 3652 (Burr Brown), are costly, generate EMI (former), and have limited bandwidth. IL300 has the advantage of design flexibility as both the photodiodes and LED are accessible to the designer, has higher bandwidth, does not generate EMI, is of low cost and easily available in the local market.

Optocouplers 4N35 (low Band Width [BW]), 6N136, and HCPL060 (High BW) have GaAs infrared LED as input and the output is a phototransistor or a combination of phototransistor and photodiode. In these devices, the optical flux radiated by the infrared LED is a nonlinear function of time and temperature and there is no way to compensate this nonlinearity. Hence, these devices are used for digital data communication.

In the following section, we give design details and test results for linear optical isolation circuits using IL300 (Vishay Semiconductors) and HCNR201 (Hewlett Packard). Before giving design details, a brief description of the basic elements of IL300 will be useful.

2.1 LED

IL300 consists of a high-performance AlGaAs infrared LED which irradiates two closely matched PIN photodiodes PD1 and PD2 as shown in Figure 2. Diode PD1 is referred to as servo photodiode which is used in servo feedback arrangement for compensating LED's nonlinear time and temperature characteristics and PD2 is output photodiode. These devices are so arranged that the LED's flux falls equally on both the photodiodes. The device gives best linearity when LED is operated between 5 mA and 20 mA [5].

Photodiodes: Both photodiodes PD1 and PD2 are PIN photodiodes. The function of these photodiodes is generation of photocurrent on absorption of optical incident radiation. PIN photodiodes have the advantage over P–N junction photodiodes that they exhibit higher speed and quantum efficiency due to their different internal structure. PIN photodiodes have centrally lightly doped intrinsic semiconductor sandwiched between P and N type diffusions on both sides. This reduces the capacitance and increases the depth of depletion region which results in increase in speed, BW, and conversion efficiency. Penetration depth of photons in a crystal is a function of wavelength and only those photons which excite electrons in the depletion region contribute to photocurrent. Electron hole pairs formed outside the depletion region simply recombine and do not contribute to photocurrent [6].

Figure 3 shows the electrical equivalent circuit of a photodiode. The diode is represented by an ideal current source IP with shunt capacitance Cj, shunt resistance Rj, and series resistance RS. The overall bandwidth of a photodiode circuit depends upon the photodiode capacitance, amplifier characteristics, and feedback network. An ideal photodiode should have zero capacitance and infinite shunt resistance.

Linear optocouplers can be used in three different configurations as described in the subsequent paragraphs. Each configuration has its merits and demerits and is chosen based upon one's applications.

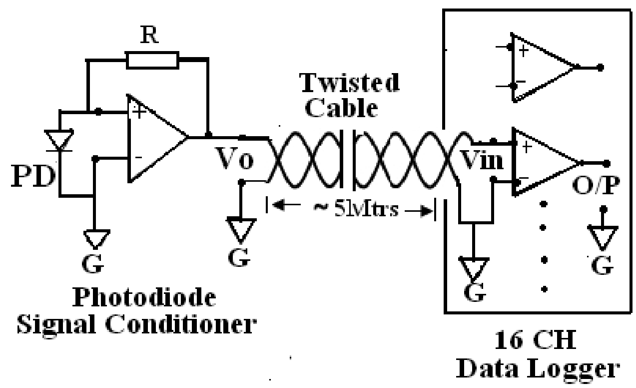

Figure 1: Setup for measuring optical power without galvanic isolation between the two grounds.

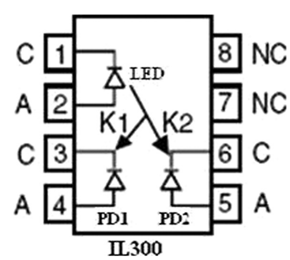

Figure 2: Schematics of optical isolator IL300.

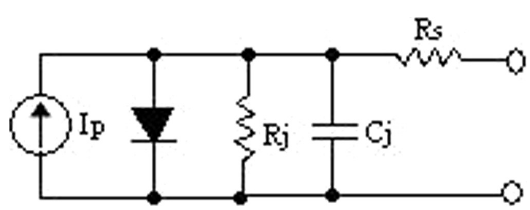

Figure 3: Photodiode equivalent circuit.

2.2 Photovoltaic Mode or Zero Bias Mode

In photovoltaic mode, the electron hole pairs formed in the depletion region by absorbing the incident radiation reach the junction by diffusion under the influence of the inbuilt potential barrier or reverse field, thus contributing to photocurrent. This mode is relatively slow because there is no external field to accelerate the electron hole pairs formed in the depletion region, and due to narrow depletion region, the conversion efficiency is also low. Though this mode has a low BW (≈50 kHz), it has better linearity and noise performance than the photoconductive mode. Figure 4 shows the circuit diagram for this mode of operation. The circuit can be used for bipolar operation by giving a DC reference voltage at the point DC ref of the circuit diagram.

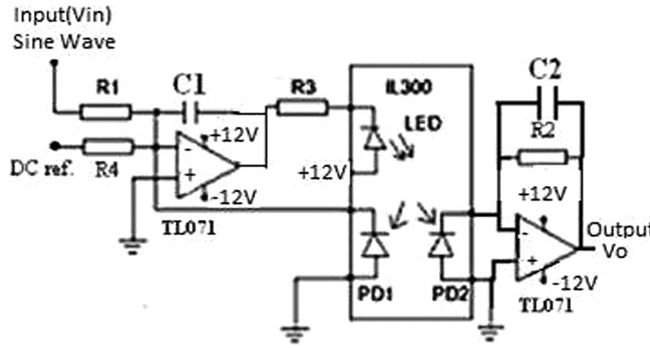

Figure 4: Photovoltaic mode.

Figures 5 and 6 depict the plots of frequency versus gain and phase shift for two different sets of compensating capacitors C1 and C2. The results show that the bandwidth and phase shifts are 20 kHz, 10° and 40 kHz, 40°, respectively. The frequency response of the circuit is determined by the product R2 × C2 and the input capacitance of the photodiode (12 pF for IL300). The peaking of gains at 150 kHz and 100 kHz in Figures 5 and 6, respectively, occurs when input capacitance of photodiode Cj and feedback capacitance C2 make an unstable amplifier. Therefore, to achieve wide frequency response without ringing and non-uniform gain, optimization of photodiode capacitance, operational amplifier's gain bandwidth product, and feedback components are required [7].

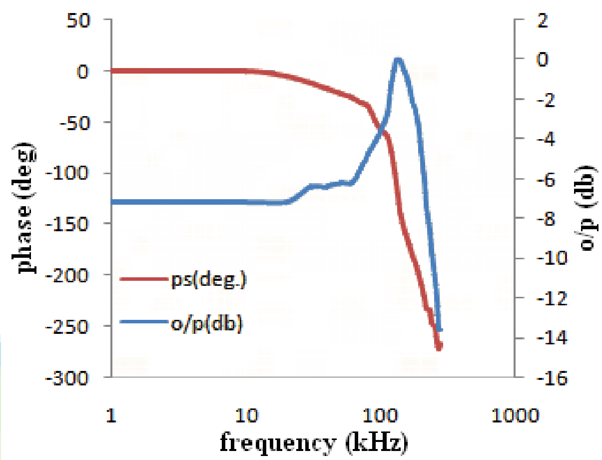

Figure 5: Frequency versus gain and phase shift for C1=C2=4.7 pF.

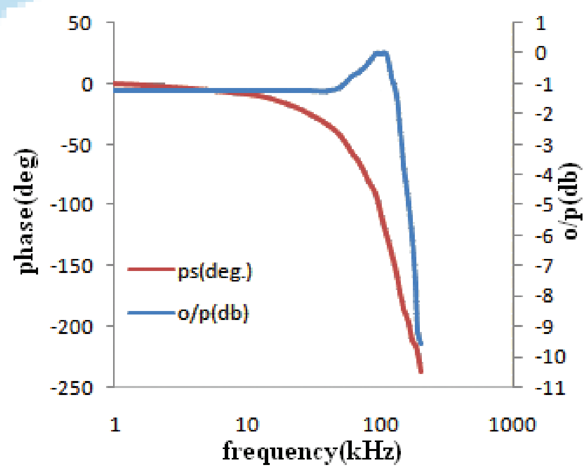

Figure 6: Frequency versus gain and phase shift for C1=C2=10 pF.

2.3 Photoconductive Mode

In photoconductive mode, the external reverse field applied across the photodiode increases the width of the depletion region and decreases the capacitance of the device. Increase in depletion region improves the conversion efficiency or quantum efficiency of the device due to increased number of photons absorbed and the reduction in capacitance increases the speed or transit time, therefore bandwidth. Though in this mode the dark current is also added to the photocurrent, this is very small (25 nA max. for IL300) and can either be neglected for most of the applications or can be subtracted from the photocurrent for precise measurements. In brief, photoconductive mode offers several advantages over photovoltaic mode [6], such as higher speed, improved stability, larger dynamic range, lower temperature coefficient, etc., but at the cost of lower linearity and noise performance.

Measurements were taken for observing the effect of reverse voltage on photodiode current with the circuit diagram shown in Figure 7. Fixed amplitude of sine wave is applied at the input, and the output voltage is measured across R2 by increasing reverse voltage VR. The results are shown in Figure 8. The graph shows that percentage increase in output voltage is 14% when reverse voltage is increased from −1 to −30 V.

Figure 9 shows the circuit where both input and output photodiodes are connected in photoconductive mode. Frequency response and phase shift for this circuit are shown in Figure 10. The graph shows a bandwidth of ~200 kHz (−3 dB) with a phase shift of −80°. The DC reference is given to make the circuit bipolar.

2.4 Mixed Mode

Figure 7 shows the circuit where input stage is in photovoltaic mode and output stage is in photoconductive mode.

We have been using this circuit for interfacing photodiode signal conditioner circuit measuring laser power at different stages of the optical table with a data logger. The output of the isolation amplifier is connected to the 16-channel data logger placed about 5 m away from the isolation amplifier on a 19″ rack. As shown in the diagram, a DC reference of 2.5 V generated by a precision reference IC LM431 is given to the inverting input of the op-amp TL071 to make the circuit bipolar without increasing the complexity and number of components (a bipolar circuit needs two IL300s and two op-amps in the input stage). Thus, the circuit can be used for unipolar as well as for bipolar inputs by simply adjusting the DC shift in the output stage. The operation of the circuit is explained in the following section.

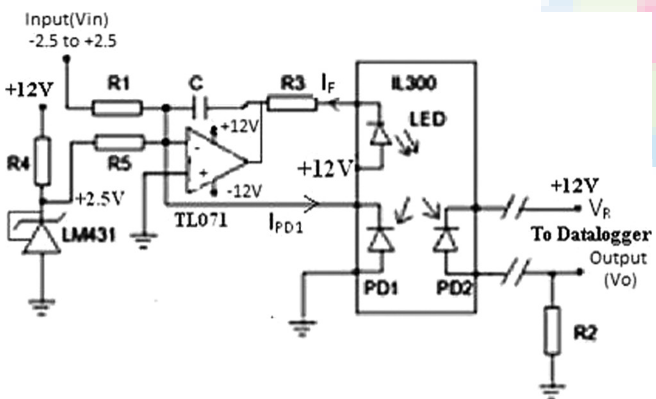

Figure 7: Mixed mode of operation, viz. I/P stage is in photovoltaic mode and O/P stage is in photoconductive mode.

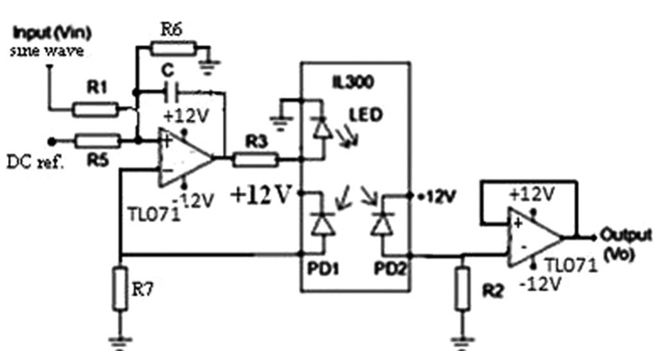

Figure 9: IL300 in photovoltaic mode.

For any input voltage, the op-amp adjusts the LED current (IF), and hence the current in the servo photodiode PD1 such that the inverting input is always at zero volt. If input voltage is increased, voltage at inverting input increases; this causes the output of op-amp to increase until the increase in LED current, and therefore current in PD1 pulls back inverting input to zero volts. Any change in the light output of LED due to temperature is taken care of by the servo current in PD1 by changing the output voltage of op-amp to maintain the inverting input at ground potential. Assuming a perfect op-amp, no current flows into its input terminals, hence the current flowing in R1 will flow in PD1 also. As inverting input is at zero volts, the current in PD1 is given by the following relation:

$$IPD1 = Vin/R1 \text{ or } \quad Vin = IPD1 \times R1 \quad (1)$$

The output voltage Vo is expressed as

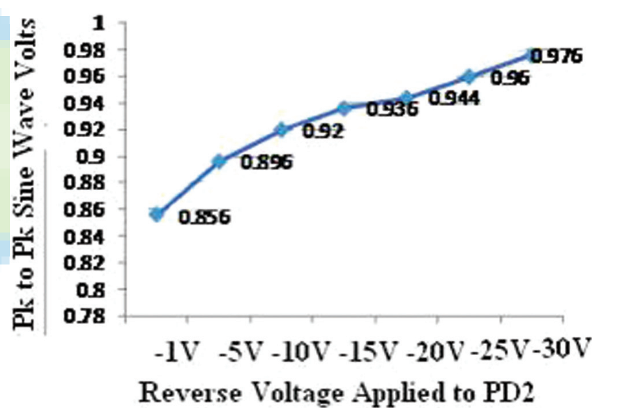

Figure 8: Effect of increasing reverse voltage on output photodiode PD2 of Figure 7.

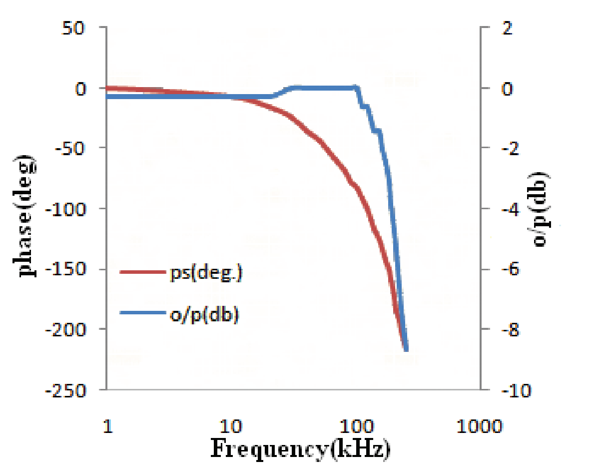

Figure 10: Frequency versus gain and phase shift for Figure 9.

$$Vo = IPD2 \times R2 \quad (2)$$

From Equations (1) and (2), -

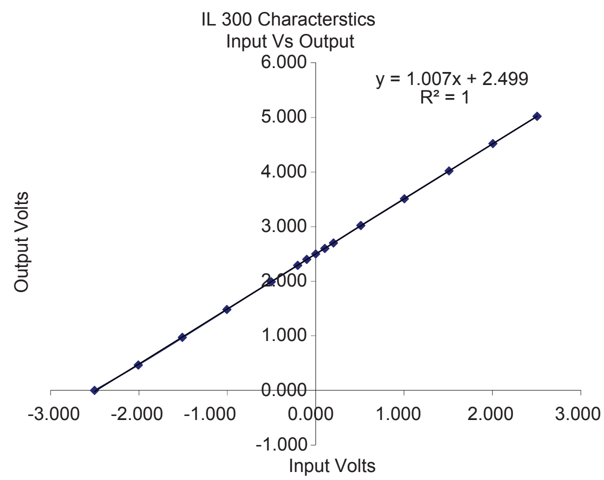

Figure 11: O/P voltage versus I/P voltage for circuit shown in Figure 7.

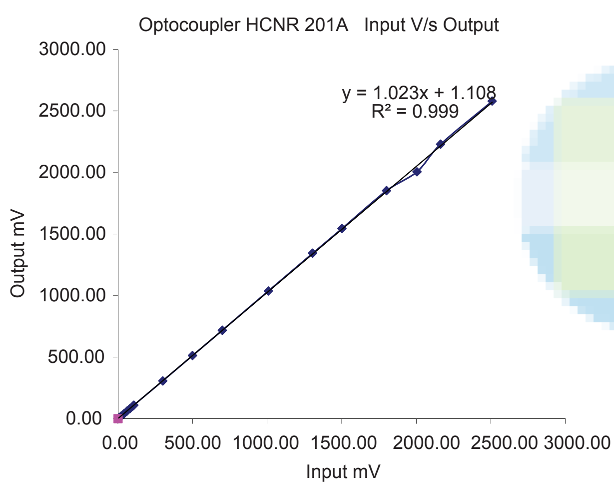

Figure 12: O/P voltage versus I/P voltage for the circuit shown in Figure 7. IL300 is replaced by HCNR201 and DC reference is made equal to zero volts.

$$Vo/Vin = IPD2/IPD1 \times R2/R1 = K3 \times R2/R1 \quad (3)$$

K3 is optocoupler gain or transfer gain and is the ratio of forward gain and servo gain. Its typical value is 1 and is also available with different gains ranging from 0.590 to 1.526 [5].

K1 is servo gain = IPD1/IF; K2 is forward gain = IPD2 IF. As K3 = constant, R2/R1 = constant. Hence, Vo α Vin.

The output voltage is directly proportional to the input voltage and does not depend upon light output characteristics of the LED.

Observations for measuring the linearity of the circuit were taken by varying input DC voltage from −2.5 to +2.5 V in steps of 0.5 V and graphs were plotted between input and output voltages for two linear optocouplers IL300 and HCNR201. The results are shown in Figures 11 and 12.

3. DIGITAL OPTOCOUPLER

In this part, we discuss application of digital optocouplers to reduce the pickup and ground loop noise problems encountered during communication between detection signal of Cs fountain and the monitoring/ controling PC.

In this design, the detection signal from the photodiode signal conditioner circuit is processed in the microcontroller and the ground of microcontroller is galvanically isolated from the PC ground using two high-speed optocouplers HCPL4502. The communication is done through RS232 protocol. The circuit diagram is shown in Figure 13. An RS232 to USB converter can also be used for communicating data through USB port of the PC.

The circuit diagram shown in Figure 13 uses dual supply. The circuit can also be designed to operate with

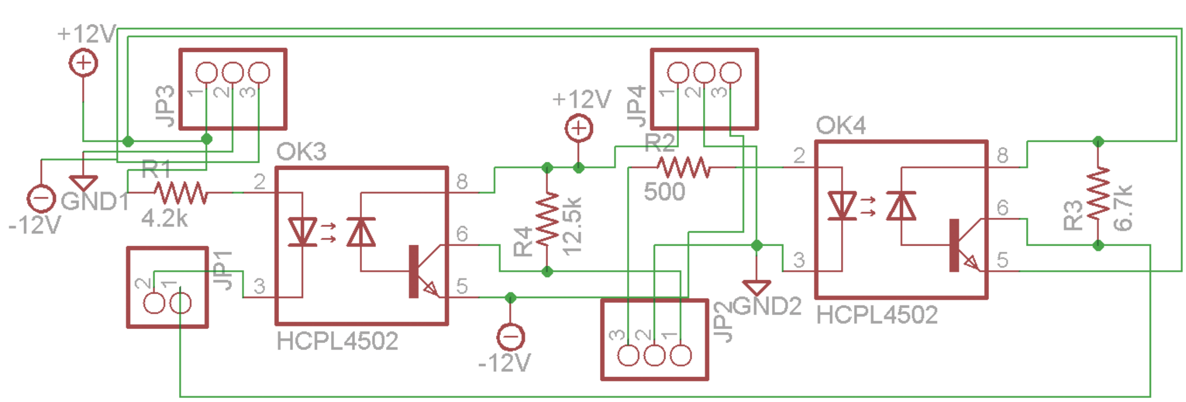

Figure 13: Opto-isolation circuit for RS232 protocol using dual power supply, where JP1 is μc Tx and Rx terminal, JP2 is PC (Tx and Rx) serial port terminal, JP3 is Supply 1, and JP4 is Supply 2.

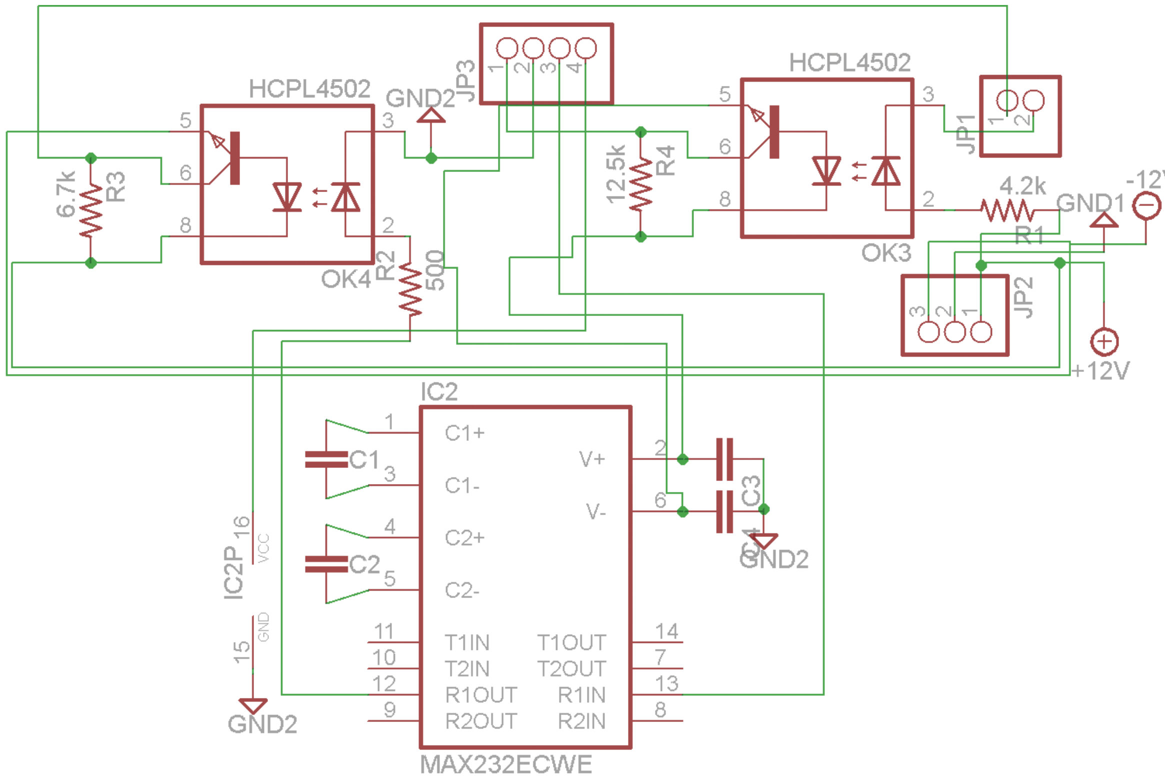

Figure 14: Opto-isolation circuit for RS232 protocol using single power supply, where JP1 is µc Tx and Rx terminal, JP3 is PC (Tx and Rx) serial port terminal, and JP2 is Supply 1.

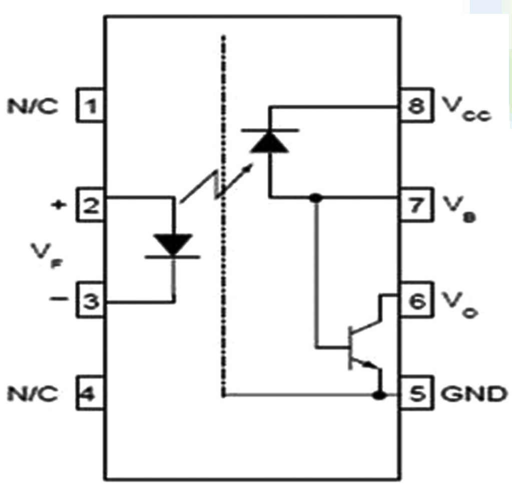

Figure 15: Schematic of HCPL4502.

a single supply as shown in Figure 14 by adding one more IC MAX232.

The schematic of single-channel optocoupler HCPL4502 is shown in Figure 15. Its input–output insulation leakage current of about 1 µA (at relative humidity = 45%, temp. = 25°C, time = 5 s, and VI-O = 3000 VDC) provides very good isolation [4,8]. Observation of noisy bit stream taken during interfacing the signal to the PC with a 5-m-long cable without ground isolation is shown in Figure 16.

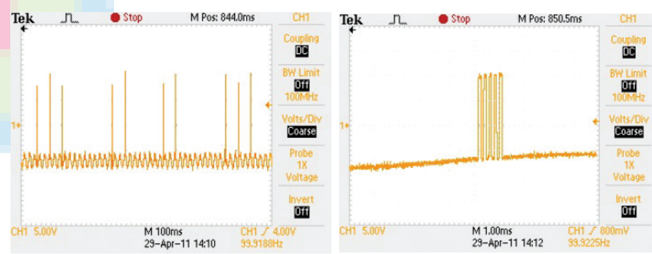

Figure 16: Noisy bit stream and its zoomed version is taken with Tektronix TDS 2012 when the grounds of signal source and PC were not isolated and the cable length was 5 m.

4. PERFORMANCE AND EXPERIMENT RESULTS

In this design, we have optimized the values of resistors to obtain best response in the aspects of rise and fall times [6-10] of pulse trains, and the circuits developed can communicate upto 57,600 baud rate without any distortions in the bit streams. Figures 16 and 17 show the bit streams while communicating with the PC with and without using the optocouplers, respectively.

Figure 18 shows rise and fall times of a pulse at 80 kbps. Experimentally we found that the circuits shown in Figures 13 and 14 work satisfactory up to 58 kbps while communicating with the PC.

Figure 19 shows the change in rise and fall times of

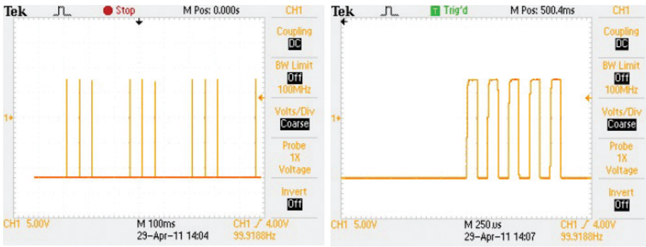

Figure 17: Noiseless bit stream and its zoomed version with galvanic isolation using IC HCPL4502.

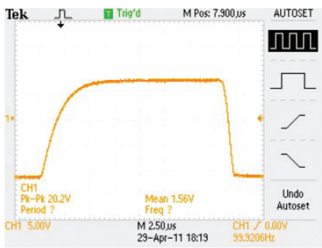

Figure 18: Rise time (≈2.0 µs) and fall time (≈0.5 µs) at baud rate 80 kbps.

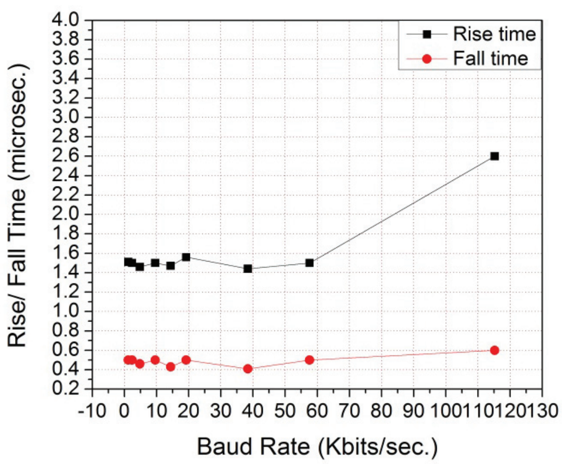

Figure 19: Rise and fall times of pulse train as a function baud rate.

pulse as a function of baud rate. The graph shows that minimum rise and fall times (tr = 1.4 µs and tf = 0.4 µs) occur at 38.400 kbps. Beyond 60 kbps, the rise time increases very rapidly, but increase in fall time is very little. We have seen experimentally that the best results are obtained at 38.4 kbps, but the circuits can operate satisfactorily up to 60 kbps.

5. CONCLUSION

A detailed description of various schemes for elimination of pickup noise and ground loop voltages encountered during interfacing signals between signal conditioner circuits sensing vital parameters of Cs fountain and monitoring systems with long cables is presented in this paper. Linear (IL300) and digital (HCPL4502) optocouplers which are of low cost, versatile, and easily available in the local market have been used. Application of IL300 in different modes, viz. for better linearity but lower BW or vice versa, is described. We have chosen these devices because they have some distinct advantages over commercially available isolators, viz. flexibility of design (compared to Burr Brown: 3650, 3656 and Analog Devices:AD210) [11] as photodiodes and LEDs are accessible to the designer for optimizing linearity and bandwidth, low cost, no EMI compared to transformer-coupled isolators. The flexibility of design can be utilized making performance tradeoffs among bandwidth, accuracy, and cost, which is difficult with commercially available amplifiers [12].

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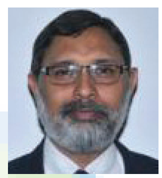

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