Journal of Engineering Research Innovation and Scientific Development
2(2): 44-50 2024, https://doi.org/10.61448/jerisd22246
Print ISSN 2971-6594 Online ISSN 2971-6608
www.jerisddelsu.com

Development of a Pulse Position Modulation-Based Optical Wireless Communication and Power Transfer System

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Article History

Received: 07-07-24
Revised: 19-08-24
Accepted: 10-09-24
Published: 15-09-24

ABSTRACT

Power management is a major problem for remotely deployed autonomous sensor devices especially in hard-to-reach areas such as in underwater applications. Motivated by the higher data rates and energy efficiency in optical communication systems, in addition to the low cost of the optical communication/ energy harvesting circuit components when compared to their RF counterparts, an efficient solution has been proposed in this work by transmitting a combination of power and information signal simultaneously through optical means and optimally separating the signals at the receiver. This proposed energy harvesting technique obviates the need for intermittent sensor device retrieval for battery charging or replacement. In this paper, we demonstrate this technique by transmitting a 3.5 kHz pulse position modulated signal using a laser diode at the transmitter circuit. At the receiver circuit, a solar panel is used for optical signal reception. The received signal is processed to separate the information signal from the power signal using an LC low pass filter. The results show that the amount of energy harvested is dependent on the combination of the amount of irradiant ambient light and the received signal itself on the solar panel, having the DC component of the harvested energy reaching 1.44 V. Additionally, at varying distances from the transmitter, the strength of the received signal itself was observed to be 0.27 V at 10 cm and reduced to around 0.20 V for distances between 60 cm to 150 cm. These results indicate that the strength of the actual transmitted signal reduces at longer distances from the receiver and confirm the feasibility of the proposed system.

Keywords: Energy harvesting, , Green Laser, Underwater optical communication; Pulse position modulation

1. Introduction

Overcoming the constraint of power supply limitation for wireless sensor nodes,especially in applications requiring remote deployment such as in underwater applications has been an area of growing interest in recent years (Filho et.al., 2020). The need to replace the batteries in these sensor nodes come as result of the finite energy capacities of batteries and also because the state of charge of a battery cannot be easily determined.

In order to overcome this constraint, various methods to simultaneously transfer information and power are being explored. Radio frequency (RF) technology can achieve both wireless information and energy transfer, even in a hostile environment (Guo, 2015).However,RF waves suffer from high attenuation in seawater and can propagate over long distances only at extra low frequencies (30-300 Hz) which requires large antennas and high transmission powers thus making them unappealing for most practical purposes (Filho et.al., 2020). Acoustic underwater communications can support transmission for long ranges up to several kilometers, they, however, are limited by bandwidth, thus fall short with their low data rates for high-bandwidth underwater applications (Kaushal, 2016). Underwater visible light communication (UVLC) has emerged as a high-capacity alternative. Since water is relatively transparent to blue or green light, blue /green visible light lasers or light emitting diodes (LEDs) can be used as transmitters for underwater wireless connectivity with data rates up to hundreds of Mbps (Ghasvarianjahromi et.al, 2019). The advantages of visible light communication (VLC) when compared to its counterparts are higher data rates, freedom from RF interference, ease of bandwidth reuse, considerable energy savings and in turn increased energy efficiency (Diamantoulakis, 2018).

A critical feature in the design of the proposed system is its energy harvesting ability. While the common choice of receivers for high-speed VLC systems is photodetectors, solar panel-based receivers have recently become an attractive alternative given its added advantage of being self-poweredand its advantage in terms of energy harvesting (Filho et.al., 2020). As a result, a solar panel can directlyconvert an optical signal to an electrical signal, without the need for an external power supply (Wang, 2015).

The common modulation schemes used for underwater environments are intensity modulation and direct detectionby which the optical power of the signal is controlled to change the pulse rate, width, frequency and/or location (Sui et.al., 2009). Amplitude shift keying (ASK), On-Off keying(OOK) and Pulse position modulation(PPM)are the non-coherent direct detection methods used as the basic modulation techniques for optical wireless systems (Suiet.al., 2009). These modulation techniquesare typically used in a simple direct detection scheme and can be implemented at low levels of complexity.Pulse amplitude modulation (PAM), as an example of intensity modulation and direct detection is greatly appealing in optical communication. However, PAM is affected by the intensity of turbulence and,therefore, is more suitable for weak turbulence conditions (Yao et. al, 2018). Although most reported underwater communication works use OOK modulation technique because it is simple to implement, OOK has shown to have the disadvantage in its power efficiency and control capacity of the error rate for underwater optical channel (Sui et.al., 2009). In comparison with the PPM, the PPMmethod is more resistant to noise than the OOK method and it does not cause a problem of threshold setting (Kang et al., 2019). WhilePPM modulation has smaller data throughput compared to OOK modulationit onlyrequires a receive power which is a fraction of what isrequired by OOK modulation to achieve the same error rate performance.

$$P_{ppm} = P_{ook} \ (1/sqrt(\left(\frac{L}{2}\right) log2L))1 \quad (1)$$

Where L is the number of bits, P_{ppm} is the receive power of PPM and P_{ook} is the receive power of OOK

Given the same transmitting power conditions, PPM could transmit at a longer distance than OOK method, which allows for an easier receiver design (Sui et.al., 2009). Hence, when taking into consideration a technique that increases the power efficiency of the system, PPM is a preferred option.

2. System Overview and Implementation

In this paper, we demonstrate the design of a wireless optical communication system capable of simultaneous power transfer using a solar panel-based receiver. To achieve this, the optical power of the transmitted signal is used for both communication and power transfer. This necessitates that the design of the receiver is one for separating the received signal to alternating current (AC) and direct current (DC).

At a transmission distance of 10m and chlorophyll levels less than 1 mg pigment per stere (mg/m³), green range indicates a better communication window while the red range shows very low signal to noise ratio (SNR) which reduced significantly as transmitting distance increased, but at increased chlorophyll levels >1 mg pigment per stere (mg/m³), the red range performs better as the green range suffers more serious attenuation in comparison (Sui et.al., 2009).Open oceans are typically characterized by lower chlorophyl concentrations ranging 0.1 to 1 mg/m³, so it is recommended that for applications involving low powered undersea systems a green laser diode-based transmitter is utilized (Kang et al., 2019). However, for coastal and upwelling regions which are characterized by much higher chlorophyll concentrations that run as high as 20 mg/m³, the red range could be a better option.

Due to the unavailability of a green laser for procurement, a red laser was employed in the experimental setup. This substitution was necessary to ensure the continuity of the experiment and obtain meaningful results despite the initial preference for a green laser.

The red laser diode-based transmitter that implements pulse position modulation is used to carry out this investigation. The design has been simplified by using a sinusoidal signal as a message signal. The sinusoidal signal is designed for a frequency of 4kHz and is generated using a buffered phase shift oscillator where the selected component values are related to the frequency by Equation 2.

$$f = 0.276/RC \quad (2)$$

The oscillator output is fed to a pulse position modulator designed to modulate at 20kHz.

The selected electronic components of the pulse position modulator were calculated using Equations 3-5:

$$\mathrm{UTP} = \frac{2Vcc -}{3} + v_{mod} \quad (3)$$

$$\mathrm{W} = -\,(\mathrm{R}_1 + \mathrm{R}_2)\mathrm{C}\ In \frac{v_{cc} - \mathrm{UTP}}{v_{cc} - 0.5\mathrm{UTP}} \quad (4)$$

$$\mathrm{T} = \mathrm{W} + 0.693 R_2 C \quad (5)$$

Where UTP is the upper transient point, W is the pulse width, v_{mod} is the voltage of the modulating signal, C is a capacitor that, along with R_1 and R_2 forms an RC timing network, R_2 is a variable resistor that allows for manual adjustment of the frequency of the output pulses and v_{cc} is the supply voltage. The modulated signal is further passed to a laser diode driver circuit which serves to supply a constant current to the laser diode whose optical output depends on the pulses of the modulated input signal.

A red laser diode of specifications; 5mW power, 2.5V maximum operating voltage, 45mA threshold current and 70mA operating current is used. The simulations were performed using Multisim. Figure 1 shows the simulation circuit used to implement the transmitter of the pulse position modulator while Figure 2 shows the corresponding hardware circuit. In the measurements, a picoscope (Picoscope 2204A) having 8bits at 100MS/s resolution and 10MHz bandwidth was used to measure the signal output from the coupled hardware. The hardware measurement set up is shown in Figure 3.

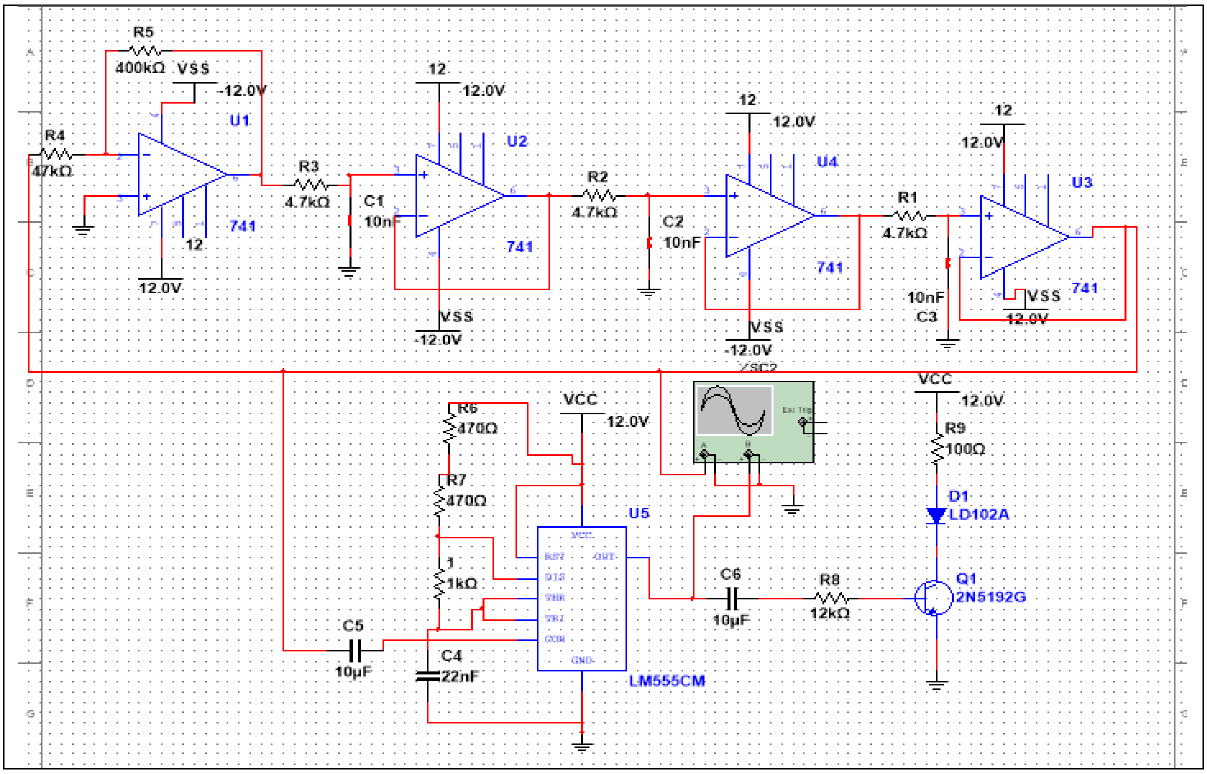

Figure 1: The simulation circuit for the laser diode transmitter circuit that implements pulse position modulation

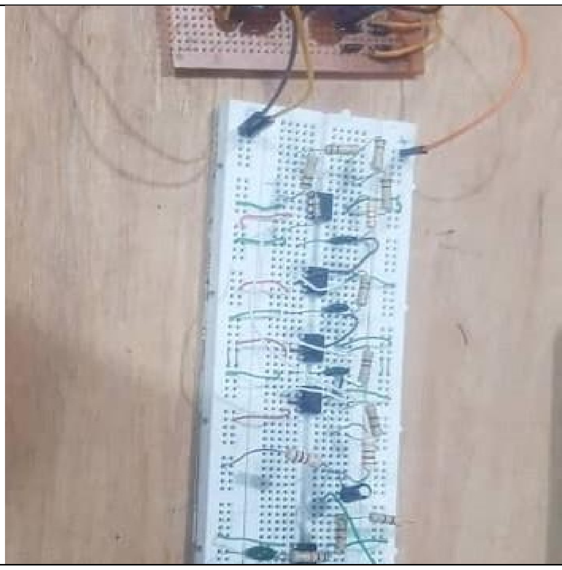

Figure 2: The implemented transmitter setup showing the oscillator coupled with the modulator and laser driver circuit

Figure 3: The measurement setup of the Wienbridge oscillator on a breadboard

A KAMISAFE solar panel with model number KM-9601A, voltage and power rating of 6V and 3W respectively, and current rating of 500mAh is used as the optical receiver. A solar panel is chosen as the photo detector over positive-intrinsic-negative photo diodes (PIN-PDs) and avalanche photodiodes (APDs) because it is self-powered and does not require an external power source to operate (Wang et al., 2015). The received modulated light is incident on the solar panel which converts it into an electrical signal. The output connectors of the solar panel are passed to the receiver circuit which consists of a passive LC low pass filter as shown in Figure 4. Most of the AC component passes through the branch for communication provided L3 and R1 are sufficiently large in comparison to 1/C1 and R2 (Wang et al, 2015). As a result, an LC low pass filter with cut-off at 4 kHz was designed.

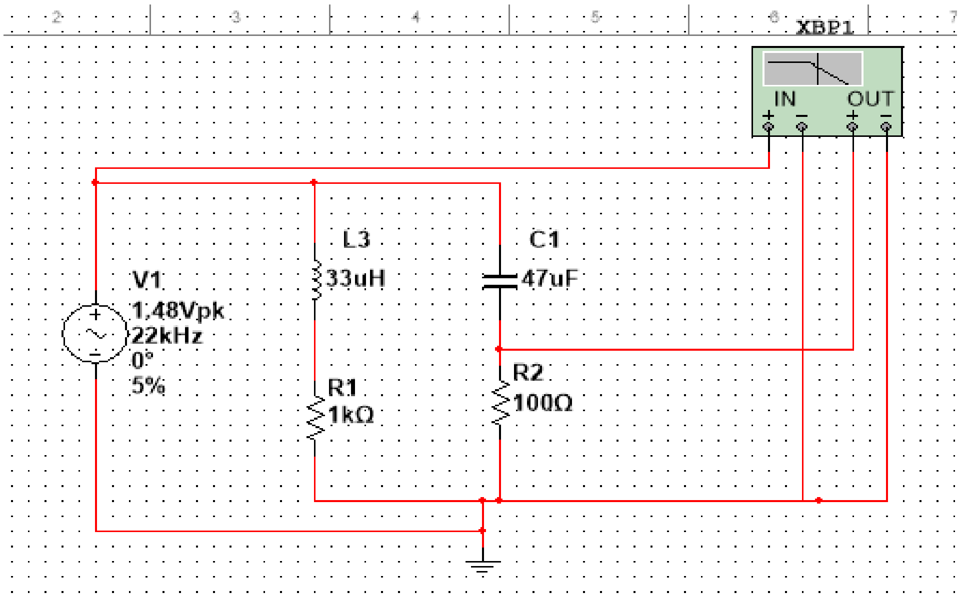

Figure 4: LC low pass filter used as the receiver circuit for separating the received signal components

3. Results and Discussion

The simulated oscillator frequency is 3.8 kHz (see Figure 5) while the output frequency of the coupled hardware oscillator is 3.5 kHz (see Figure 6). Also, simulated modulating frequency is 20.8kHz while the experiments produced a frequency of 21.8 kHz. The results from the experiments are close to the theoretical and simulated values. The readings of the experiment were taken in a brightly lit laboratory. The irradiance of ambient light incident on the solar panel was measured and recorded before experimental readings were taken. It can be seen in Table 1 that at varying distances of the solar panel from the transmitter between 10 cm and 150cm, the strength of the received signal was observed to be at a value of 0.27V at 10cm from the solar panel, but from a distance of 60cm from the transmitter up to 150cm, the strength of the received signal was observed to be around 0.20V. Thus, it can be inferred that the strength of the actual transmitted signal, when the ambient light has been considered and subtracted from the received value at longer distances away from the laser diode transmitter reduces.

Table 1: Measurements of received signal voltage with and without ambient lighting over different transmitter to receiver separation distance.

Distance (Cm)	Without light (V)	With light (V)	Transmitted value (V)
10	1.73	2.00	0.27
30	1.77	2.01	0.24
60	1.79	1.99	0.20
90	1.78	1.99	0.21
120	1.81	2.02	0.21
150	1.81	2.01	0.20

At the outputs of the receiver circuit, the DC component of the signal extracted from the energy harvesting branch as shown in Figure7 is of a value 1.44V, and the recovered modulated form of the information signal as shown in Figure 8 is a highly attenuated form of the modulated signal transmitted shown in Figure5. From the results obtained, it shows that the process of simultaneous optical information and power transmission using a solar panel receiver is feasible. However, while it is observed that the energy harvested in this experiment appears to be a combination of the ambient light and the received signal itself, with a smaller percentage of the energy from received signal itself, this is attributed to the use of a low power output laser diode of 4mW in this experiment. To improve the strength of the received information signal and eventually that of the harvested energy in application, the use of a laser diode with a higher power output should be employed. Additionally, the received information signal is observed to be highly attenuated and would require the use of an amplification stage before a further analysis such as demodulation of the signal could be carried out. The harvested energy can be utilized for the charging of a battery which could in turn power the amplification stage.

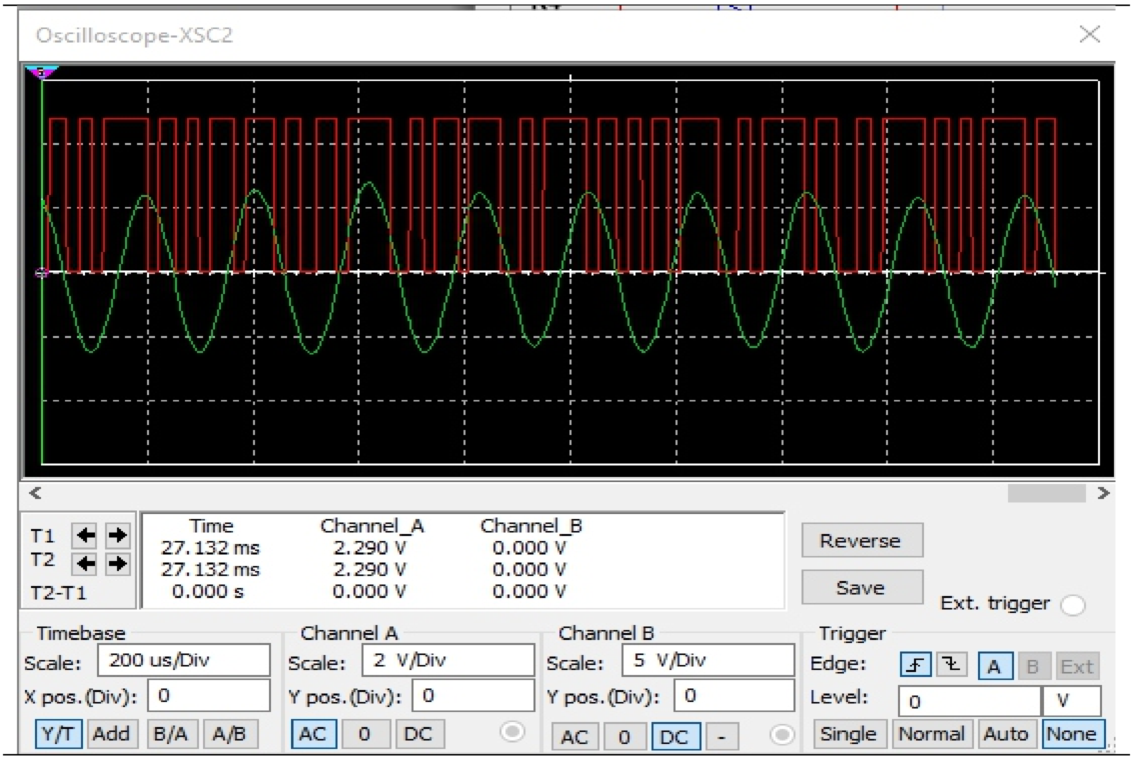

Figure 5: The output waveforms from simulation of the transmitter circuit showing the sine wave in green and the PPM signal in red

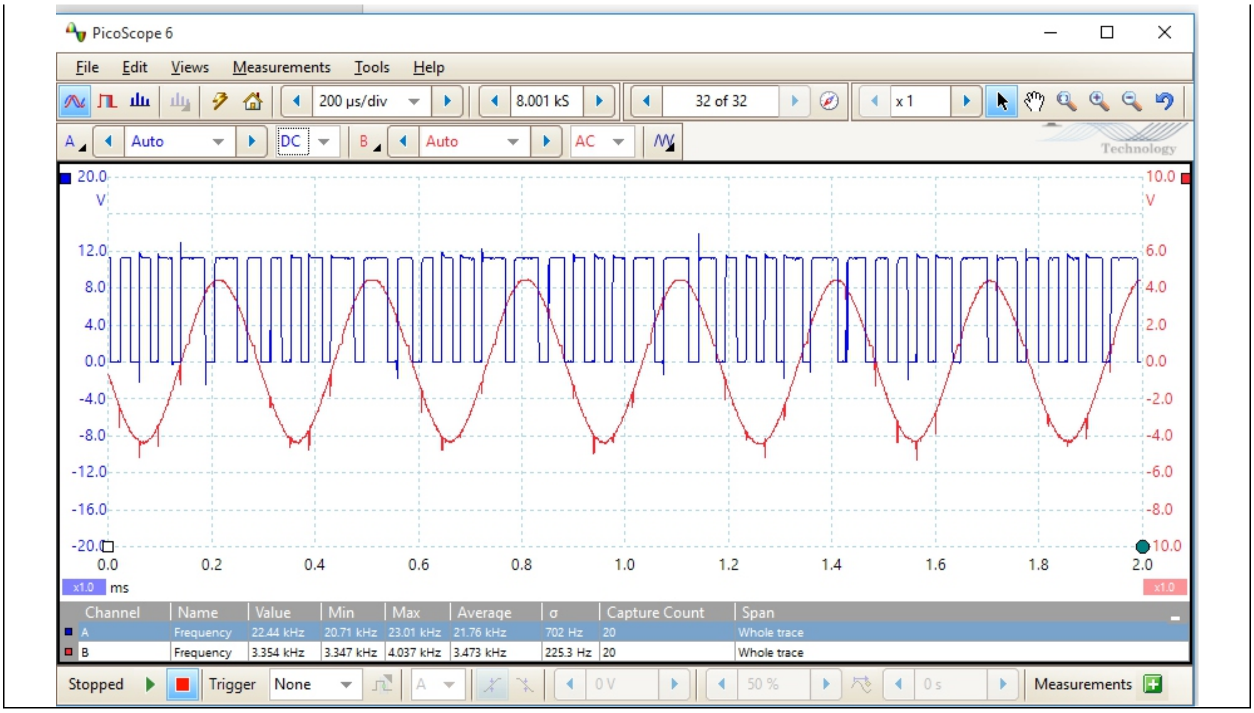

Figure 6: The output waveform from the implemented transmitter circuit on the oscilloscope showing the sine wave in red and the PPM signal in blue

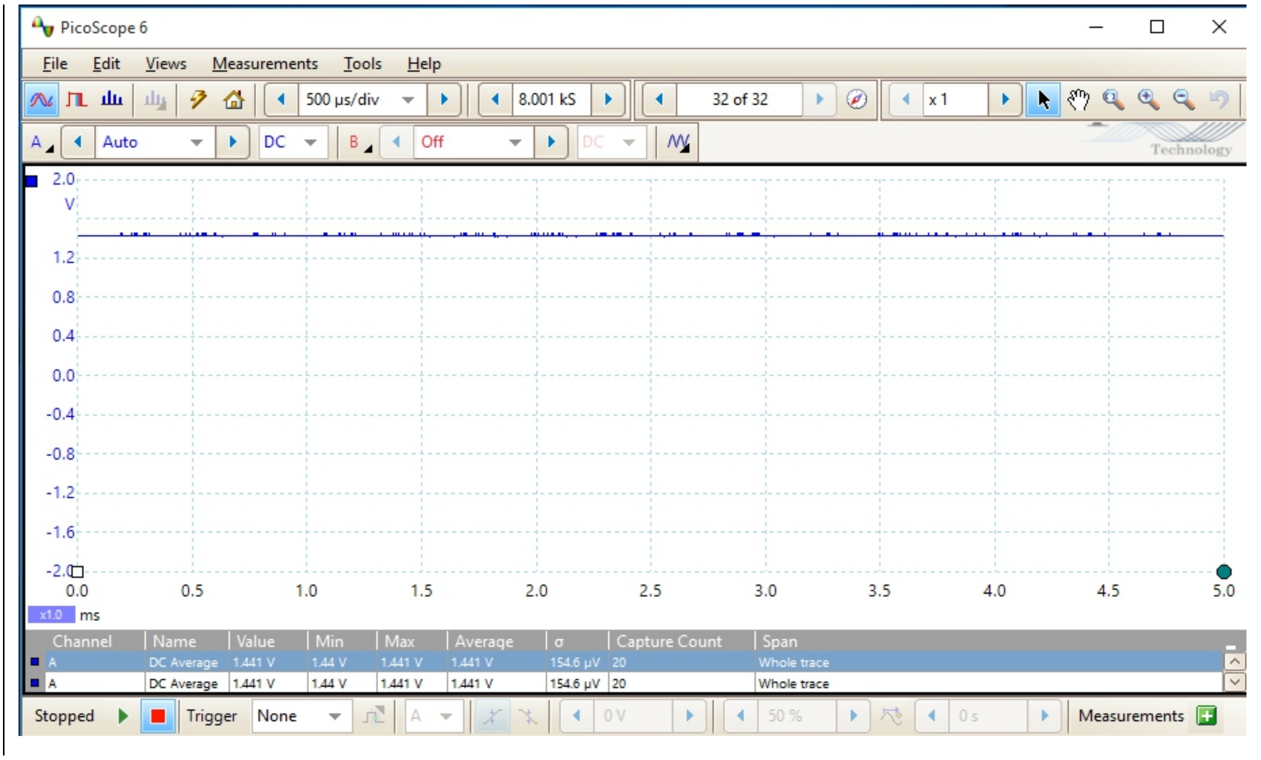

Figure 7: The output from the energy harvesting (inductor) branch of the receiver circuit

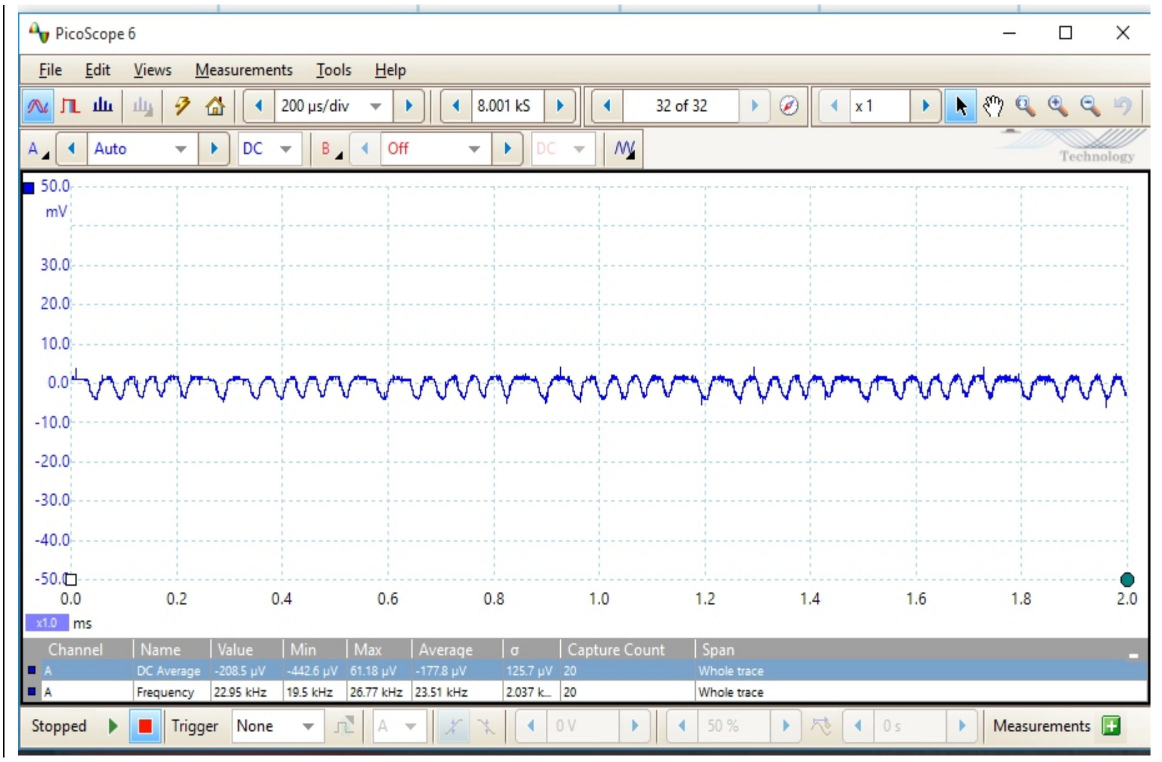

Figure 8: The output from the information recovery (capacitor) branch of the receiver circuit

4. Conclusion

This work has demonstrated the design of an optical simultaneous information and power transfer system. The system was achieved by implementing pulse position modulation (PPM) , utilizing a laser diode as the optical light source and utilizing a self powered receiver such as the solar panel. The PPM scheme is proposed in this paper as against the commonly implemented OOK as it can transmit at longer distances than the OOK scheme at the same transmitting condition. A solar panel is also proposed as the receiver since it does not require an external power source, thus reducing the power requirement of the proposed system. The energy harvesting and information recovery capability of this system was investigated under laboratory conditions. A signal voltage of 1.44V was recovered from the received signal while the filtered information-bearing signal showed significant attenuation when compared to the transmitted signal. The results are important and the developed system could be applied in sensor applications in remote locations.

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