Absorption Dependent Intensity Detector for Chlorophyll

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***Abstract* — Spectrophotometers utilize a range of select wavelengths that allow them to detect the presence of certain chemicals, compounds, or elements dissolved in aqueous solutions that we will refer to as impurities. Spectrophotometers exploit the absorption and transmission profiles of such impurities to show a distinct difference in the intensity of the incident light versus the received light, after passing through a sample containing the impurity. We developed a system that engages this concept to detect Chlorophyll A and Chlorophyll B impurities present in a water sample. The primary physical property that will be used to determine the presence and quantities of chlorophyll impurities will be the Lambert-Beer Law, which highlights the ability to calculate the concentration of a substance when both input and output intensities are known in adjunction with the chemical absorption coefficient. The design's ability to detect chlorophyll concentrations will allow users to detect the amount of photosynthetic material present in just about any organic material. Indicators of photosynthetic capabilities can be used to better understand organic materials and their macroscale impact on surrounding environments.**

I. INTRODUCTION

To begin, we'll cover some of the motivations behind our design. Fresh water, in Florida for example, varies over time in its phytoplankton concentrations. As phytoplankton in water increases, the water appears more green, indicating higher levels of chlorophyll content. The chlorophyll impurities can be sparse, sometimes being measured at just a few parts per million in concentration.

The chlorophyll content of fresh water lakes, rivers, swamps in our ecosystems are great indicators of environmental stability and can provide insight into phytoplankton populations which serve as the fundamental basis of countless biological energy cycles.

We have designed an Accessible Spectrometer for Water Impurity Detection. The purpose of our design is to identify concentrations of Chlorophyll A and Chlorophyll B impurities in fresh water samples. Current spectrophotometer devices are generalized to detect a wide range of chemicals and compounds, requiring extremely sensitive designs to accomplish. This makes most spectrophotometers relatively expensive, ranging from $10,000-15,000, which defaults such tests to third-party companies to administer.

Our device is a commercially affordable device that focuses on the ability to detect just two types of impurities. Our device puts the capability of detecting chlorophyll concentrations in the hands of retail buyers. It is designed to be a table-top, plug-in device and it is expected to be as user-friendly as most common household appliances. The user will be able to scan for chlorophyll compounds in their respective environment's water sources. The device will inform the user of the amount of chlorophyll in the provided water sample being scanned.

II. SPECTROMETER DESIGN

The objective of this design is to identify contaminants in environmental water; namely, Chlorophyll A and Chlorophyll B.

The design relies heavily on spectrophotometry concepts. Spectrophotometry is the chemical identification of substances based on the intensity distribution of light that passes through a sample. Spectrophotometric devices typically use a broadband source of light that is then separated into its component parts by a diffraction grating, prism, or other wavelength dispersion techniques. Our design does not utilize a broadband light source that is then split into its component parts by a diffractive optic. Instead, for the sake of simplifying the design and reducing costs, we utilize three select colored light emitting diodes (LEDs) that emit light at the following wavelengths: 660 nm (Red), 505 nm (Green), 430 nm (Blue) [1], [2], [8]. The LED light is then directed, in a controlled manner, towards a test sample containing chlorophyll dissolved in aqueous solution, and a control substance containing distilled water. The transmittance of the listed wavelengths are compared between the control substance and sample to identify the influence the impurities have on the light incident on the samples. The ratio at which the input light is able to penetrate the sample to be measured upon a photodetector is considered the transmission efficiency of the sample. The ratio of input light not measured by the photodetector is considered the absorption efficiency.

Another quality that makes our device different from other industrial products is that we utilize only the visible spectrum of light to identify impurities. This does come at the cost of limited capabilities, but it is a much cheaper option that still allows the user to determine a chlorophyll due to chlorophyll's absorption spectra. Chlorophyll A has absorption peaks at 420 nm and 680 nm while Chlorophyll B peaks at 480 nm and 630 nm.

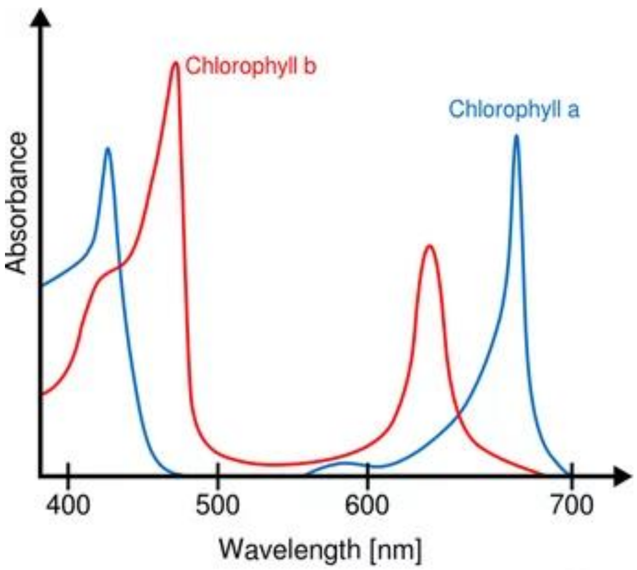

Fig. 1. The relative absorption spectra, in the VIS spectrum, of Chlorophyll A and Chlorophyll B are depicted in the figure above.

The diodes selected emit light at wavelengths that maximize the absorption effects of both Chlorophyll A and B but also provide enough bandwidth to allow the device to differentiate between the two if both substances are present in a single sample. For example, the red LED at 660 nm was selected due to the high absorption of Chlorophyll A in contrast to Chlorophyll B which has practically zero absorbance at that wavelength. Due to the broadband nature of our LED, however, which emits light in a range of approximately 30-40 nm, we can still detect absorption effects of Chlorophyll B using the 660nm red LED. We only need to take into account the varying wavelength output intensities of each selected LED, which were provided in the device data sheets.

Lambert-Beer's Law will be one of the primary physical laws that will be utilized in our design. Our system will be designed to obtain quantities for absorption (A). The optical path length (L) will be a value given by our selected sample container. The extinction coefficient will be pulled from a preloaded database for select impurities we wish to identify. Obtaining an absorption spectrum of a sample will allow us to determine which select substance extinction coefficients to select given the absorption encountered at specific wavelengths and an understanding of which impurities are most common in our selected sample. This leaves C, the concentration of the substance, which the final design will be tuned to calculate for the user.

There are other technical influences that typically need to be accounted for in the output intensity (i.e. scattering losses, reflection losses, etc.) But influences from these can be eliminated in our calculations by utilizing a test and control sample simultaneously setting the only variable between tests to be the chemical compound present in the test sample. As mentioned, we will be utilizing wavelengths of light in the visible spectrum. This will consist of dispersed light from a general white light exiting a grating/prism as well as a varying set of colored LEDs. We considered the use of acoustic and electro-optic modulators, but due to their expensive costs to produce the level of accuracy needed for our design, we opted not to use it as a wavelength selection device. Our current methods will allow us to scan a sample between 400-700 nm in 50 nm intervals.

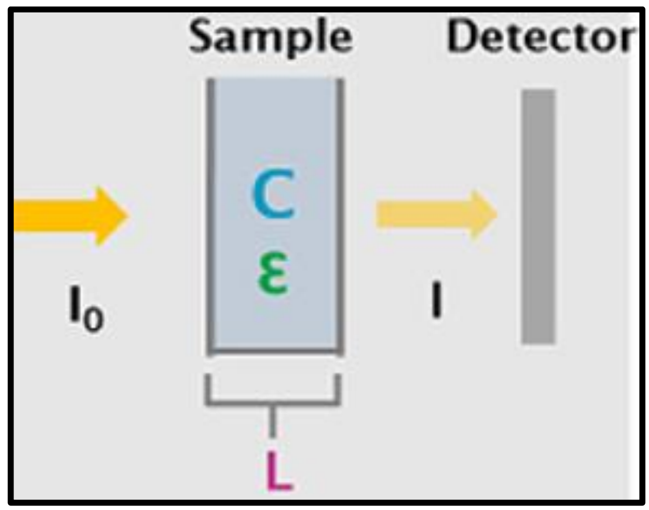

Fig. 2. The Lambert-Beer Law is shown in principle, where a certain light intensity is measured after being sent through a sample which is being tested.

The light intensities read by the photodiode for the control and test samples will need to account for the wavelength specific variations of the input light source as well as the responsivity of the selected photodiode. The figures below showcase the output spectrum of the blue 430 nm LED and the wavelength responsivity of the selected photodiode. Already, we see variations in chlorophyll absorption, LED emittance, and photodiode receptance spectras: all of which will need to be normalized to produce consistent measurements utilizing three distinct wavelength groups at 660 nm, 505 nm, and 430 nm.

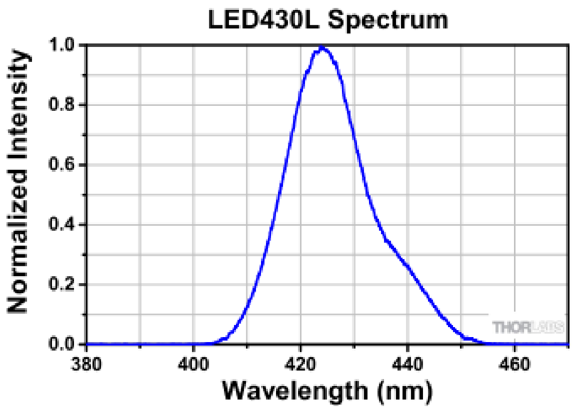

Fig. 3. This figure showcases the LED430L normalized output intensity. This spectral profile varies from LED to LED and will be accounted for when calculations are performed by the microcontroller unit to calculate impurity concentrations.

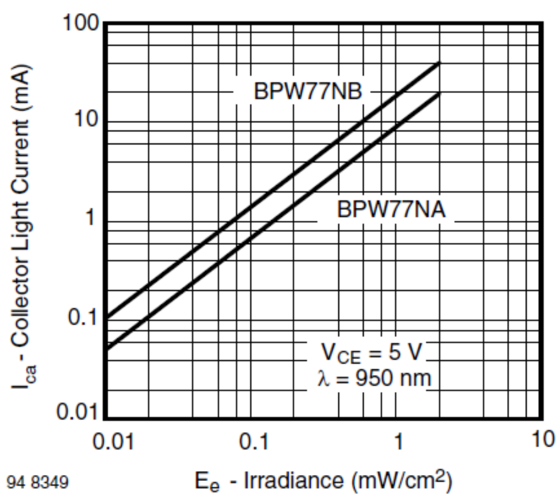

Fig. 4. This figure shows the response of the collector current to irradiance incident on the phototransistor we are using, BPW77NA.

As mentioned, a control sample will be utilized in our design. This control sample will account for any transmission influences due in part to the water or glass container that each sample will incorporate. This allows us to place additional emphasis on the independent variable, the chlorophyll in each test sample, as the only variable being changed in each test by our device.

Care must be given to interpreting the results from the control sample to understand concentrations to other samples, however. In the figure above, one should note the logarithmic relationship between incident light and the current output, which could be tricky to anyone wanting to accurately interpret measurements on the output. With the logarithmic scale in mind, we are able to more intelligently set control concentrations, where we can provide a guide to users based on informative tests that we carry out. This will ensure proper and accurate use of the spectrometer.

III. ELECTRICAL DESIGN

For our device the main electrical design can be broken into three main components with the Raspberry Pi Pico for collecting and displaying the data to our display. The first component is our battery charging circuit, the second is our 3.7 V to 5 V DC convertor, and the third is our transimpedance amplifier. The electrical design converts the power from a standard USB connection to charge the battery and power the Raspberry Pi Pico as well as the display with the transimpedance amplifier amplifying the voltage signal from the phototransistor and the DC convertor for powering the LEDs in the optical design.

Further details are provided in the remainder of this paper for specific situations.

A. Battery Charging Circuit

The battery charging circuit is responsible for both converting the 5 V charge from the USB to 3.7 V as well as charging the lithium-ion battery. This means we needed an electrical circuit design that could be able to do both and have an appropriate charge for the battery. For this we used the Texas Instrument WEBENCH designer online to create the circuit. We decided to use the MCP73831 battery charger controller to be the heart of the circuit and used its reference circuit along with WEBENCH to create the necessary circuitry. This circuit can accept between 5.5 V to 4.5 V well and send out an output between 3.3 V to 3.7 V and this is within the safe operating parameters of our lithium-ion battery and the USB connection we are using to receive the power from the outside.

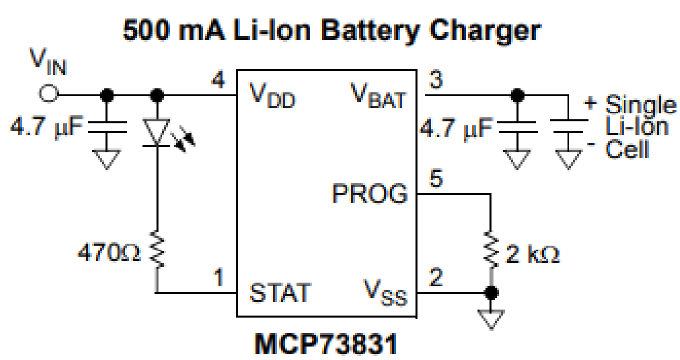

Fig. 5. Microchip provided a reference circuit for a typical application of the MCP73831 with input voltage 3.75 V to 6 V to charge a 500mA lithium-ion battery charger that was used to reference for the design

B. 3.7 V to 5 V DC Converter Circuit

The 3.7 V to 5 V DC converter circuit is used to convert the voltage from the battery to the necessary voltage and current needed for the second USB connection. The circuitry was made with the Texas Instrument WEBENCH tool just as the battery charging circuit was. This was done to make sure to get the most efficient piece for the best price. The circuit is centered with the TPS61256 load boost converter. from Texas Instrument. The load convertor is the part that is responsible for adjusting the voltage to the necessary voltage needed for the USB connection for the LED. The necessary voltage range is 2.5 V to 4.2 V for the input to the load boost converter which means the 3.7 V from the lithium-ion battery and then it is boosted to 5 V that is needed for the LEDs to work at their most efficient period.

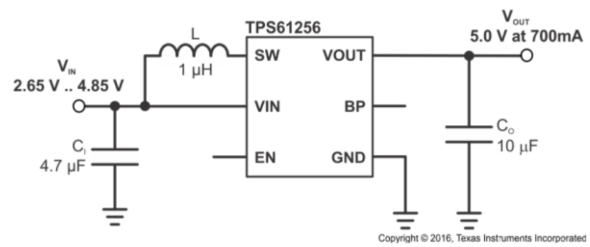

Fig. 6. Texas Instrument provided a reference circuit for a typical application of the TPS61256 with input voltage 2.65 V - 4.85 V to receive a 5 V output that was used to reference for the design.

C. Transimpedance Amplifier Circuit

The output from the phototransistor is an essential step in accomplishing our measurements. The phototransistor in question, which is how we transform optical power transmitting through our substance into electrical current to be able to be read in our circuit, only outputs a small amount of current. More about this phototransistor can be found in section V, Photodetector.

In order to overcome the limiting factor of the photodetector current, which would only output voltage on a scale of millivolts to be read by a voltmeter, we construct a transimpedance amplifier circuit, which can be seen below. This circuit can amplify this voltage to up to 10 volts.

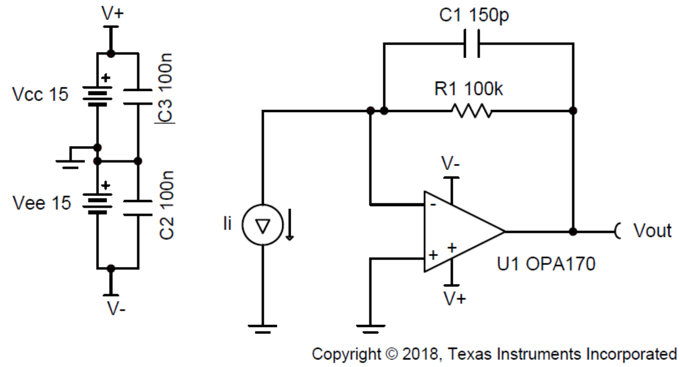

Fig. 7. Texas Instruments example of a transimpedance amplifier, which was used as a template for our circuit. Please note that we used approximately 6 V for supply voltage and a different operational amplifier.

When the voltage is taken across the outputs, we can move the measurement forward to the next step of the overall electrical design which is specified in a later section: “Raspberry Pi Pico.”

IV. OPTICAL DESIGN

Since our wavelength specific LEDs have a viewing half-angle of approximately 20 degrees, which is the point where the intensity of the light is exactly one-half what it would be at 0 degrees, we utilized a set of plano-convex lenses as part of our optical design. Using 25.4 mm (1 inch) diameter lenses with a focal length of 25.4mm allow us to produce a collimated beam of light at each 430, 505, and 660nm within the diameter constraints of the collector lens when the lens is placed a focal length’s distance away from each LED.

The use of plano convex lenses, allow us to collimate our LED light, pass it through a predetermined volume of a water sample (approximately 38cm^3) hosting a concentration of chlorophyll, and collect the transmitted light to direct towards the photodiode receiver circuit. According to our calculations, if we treat the LED as a point source, and filter out excess light traveling outside the viewing half-angle of the LED by way of an optical aperture, by placing a 25mm focal length plano convex lens one focal length away from the LED, we can create a collimated light source with a beam diameter of approximately 20mm. Our lenses were selected to have diameters of 25.4mm, so all of the emitted light can be collected by the secondary plano-convex lens. The focal lengths of each lens were hand selected so that the size constraints of our design objectives could be met.

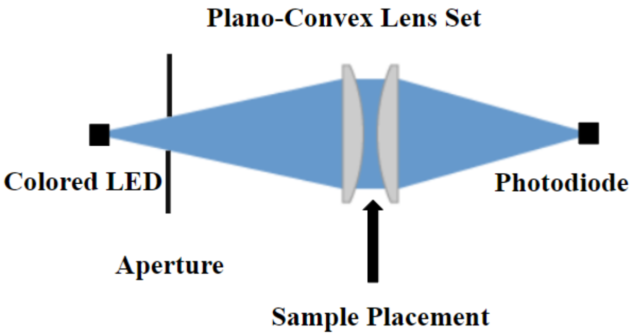

Fig. 7. This figure showcases the optical design utilized in the device. A plano convex lens set is applied to collimate the LED light within the constraints of a 25.4 mm beam diameter. Note: this figure is not to scale. Also note: the optical design is applied in a top-down vertical fashion in the construction of the end product.

Give an expected collimated beam diameter of 20 mm throughout the area of the sample placement. We can calculate the expected volume of light that passes through the water sample given a sample length of 60 mm. The volume where absorption takes place is approximately $38cm^3$. This value will be utilized within the device's microcontroller unit in coordination with the Lambert-Beer Law so that theoretical predictions of chlorophyll concentrations can be determined by the device.

In the device, the optical components will be positioned vertically. The LED will be illuminating the sample from the top. Each lens will be held in place by the chassis against gravity so that the angular, lateral, and longitudinal placement will be secured. The sample will be able to be adjusted, removed, and replaced without interfering with any of the peripheral optical components. By doing this, we ensure that the optical design remains on-axis and that no additional variations between the tests are added with each sample test. This allows us to perform one 'control' test with a distilled water source, whose measurements and data will be stored within the microcontroller unit, to reference against any following sample tests.

The optical design will be fully encased in a 3D printed chassis. The chassis will be completely oblique, to block any excess ambient light from interfering with the device photodiode measurements.

V. PHOTODETECTOR

Previously, we discussed the intelligent use of the light moving through the system. Now, we will discuss the way that light will be utilized in producing a measured output. This is done by the utilization of the subject of photosensing. Some technologies in this field use different strategies than others.

Photoresistors are an example of this technology, and they involve using a material with valence electrons sensitive enough to incident light that they are ejected from their parent atom and join the conduction band. Light is therefore measured by the degree of conduction of electricity through this material. Photoresistors are not semiconductors, like the technology we used, and are also less light sensitive than we desired [3].

For this design, we decided to utilize the concept of photodiodes, specifically the technology of phototransistors. These are semiconductors that are sensitive to light. Photodiodes, being semiconductors, have PN junctions, which react to incident light by producing a photocurrent across the device, which provides current to the circuit, which can be measured.

Phototransistors are different from photodiodes in that they involve different constructions of their junctions. Photodiodes are usually either PN or PiN junction semiconductors, and they involve a smaller photocurrent generated from incident photons. A phototransistor, however, is a bipolar junction transistor that is of the form NPN most popularly [5]. An NPN phototransistor has an amplified photocurrent due to its construction. Because we are looking for the largest photocurrent to take in and measure, we chose the phototransistor.

A. Phototransistor BPW77NA

The phototransistor we are using is Vishay Semiconductors' Silicon NPN Phototransistor, BPW77NA. This phototransistor has a good resilience to maximum voltages and currents, which made it easier to work with while designing our device, meaning we would be less likely to break it. Additionally, it works well in the visible spectrum wavelength, which is essential for our spectrometer.

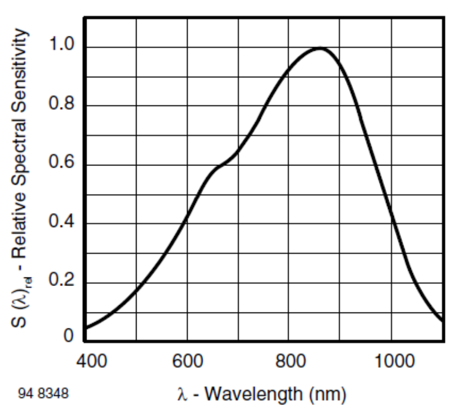

Fig. 8. Relationship between incident-light wavelength and sensitivity of the phototransistor, relative to its sensitivity at a wavelength of 950 nm. Taken from reference [6]

Above is a graph from the specifications sheet for the phototransistor we are using. It shows an effective spectral sensitivity across our desired wavelengths, with a conversion factor to ensure these wavelengths are measured with consistency according to their effect on the phototransistor.

B. Amplifier Circuit

The nature of phototransistors is that very little current is created from the photosensitive area. The active area is small, and the semiconductor can often have a very small acceptance angle for light, which further decreases the efficiency of photocurrent creation. This is why an amplifier circuit is necessary to resolve measurements from the light resulting from the absorption process in the water/chlorophyll.

This circuit involves the creation of a photocurrent in the phototransistor, which moves through the circuit to then be amplified across a resistor to be measured as a voltage. This voltage is taken from the amplifier circuit to be measured later. The circuit in question is more electrically defined in section III, “Electrical Design.”

Effectively, what is output is on the scale of millivolts if it were to be read across a resistor on our voltmeter. With an amplifier, we aimed to get the voltage to a scale of 3.3 volts, which is a specification of our design that is due to the functionality of the Raspberry Pi Pico. The amplifier is actually capable of converting the small and difficult-to-read current from the phototransistor to up to 10 volts when read across the output. This would be too much, so we decrease the voltage supply across the operational amplifier to achieve our intended voltage scale.

VI. RASPBERRY PI PICO

For design we need a microcontroller unit that is able to handle the calculator and computations that are necessary to complete our goals and objectives that we specified early in the second section. The Raspberry Pi Pico is a development board that uses the RP2040 microcontroller for the central hub and calculation systems. It has 40 pins that include 26 multifunction GPIO pins, including 3 analogue inputs 2 × UART, 2 × SPI controllers, 2 × I2C controllers, 16 × PWM channels 1 × USB 1.1 controller and PHY, with host and device support ,8 × programmable I/O (PIO) state machines for custom peripheral support. The Raspberry Pi Pico utilizes a built-in micro-USB power system that uses an input voltage range of 1.8 V to 5.5 V. This input voltage range is what lets us create the power supply schematic that was created with our battery charging circuit and DC to DC converter to power the Raspberry Pi Pico externally rather than through the built in micro USB. The micro USB will be used instead to drag and drop code into the microcontroller to collect and calculate from the phototransistor.

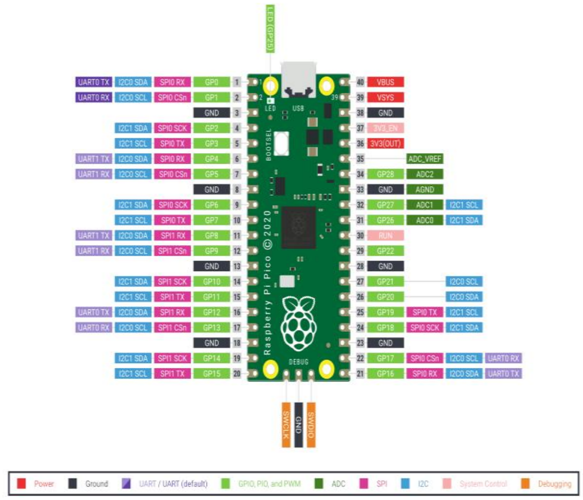

Fig. 9. The provided pinout sheet for the Raspberry Pi Pico shows all the pins that are able to be utilized in the circuit as well as the known ground connections provided by the Raspberry Pi Pico spec sheet.

The Raspberry Pi Pico will receive the information from the phototransistor into pin 31 that comes from the transimpedance amplifier talked about earlier in the electrical design. Pin 31 is used as it is one of the pins that can accept voltage as its one of the programmable pins in the Raspberry Pi Pico. To measure the voltage coming from our phototransistor we compare the voltage with the 3.3 V that can come from our Raspberry Pi Pico in pin 36. This was done by creating a rudimentary potentiometer by connecting it over a 5 kilo ohm resistor that is used to measure the difference of the voltage so that we can get an accurate reading from the phototransistor.

The Raspberry Pi Pico will also be connected to our display so that we can show the end result of our calculations. The display we will be using is the HD44780 IIC I2C1602, a 16x2 Liquid Crystal Display that can be used to display the information that we want to display to the end recipient. It is connected to the Serial Port Interface through pins 1 and 2 this will be used to connect the information that is being sent from the Raspberry Pi Pico. The display will be powered from the Vbus pin on pin 40 this is because that is the only port that can utilize a 5 V connection that is needed to power the display.

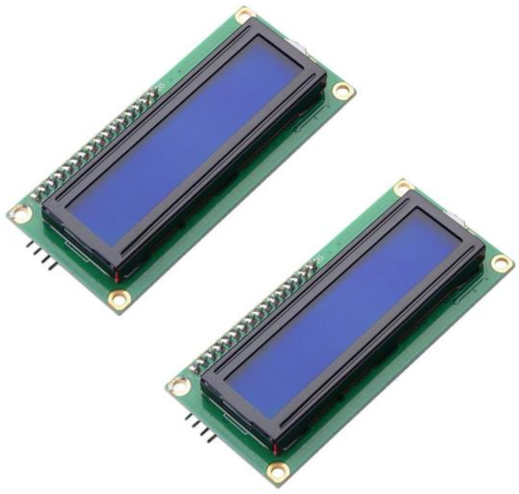

Fig. 10. The HD4478 IIC I2C1602 is the display that will be utilized for the project. The pins that are utilized are the 4 pins on the backpack SPI.

The Raspberry Pi Pico has a small amount of built in memory with 264KB of SRAM, and 2MB of on-board Flash memory. This allows the Raspberry Pi Pico a small amount of processing power to run small calculations that were needed for this project to be successful. The calculations were done using micropython as the coding language for the software development. The specifics of the coding and software development will be expanded more on in the software section of this paper.

A. Programming the Reception to Output

In order to receive and make use of the information that is acquired through the process of designing this device, we must interface said information to the rest of our information technology or the user. We decided, as seen before, to interface the output of information to the user through the LCD screen, but in order to do that, we must first control the flow of information from the device to the LCD screen.

The computer interface with the Raspberry Pi Pico is effective in providing the capability to easily control the flow of the data as it is being read by the Raspberry Pi Pico from the phototransistor. The programming language Python is used in this case, through the integrated development environment (IDE) Thonny. With this, code can be written directly to the Raspberry Pi Pico and executed on the device itself to direct data to display on the LCD screen.

The matter of writing code to the device follows a few steps: first, one must define a class from which functions can be utilized to perform the tasks we need to be accomplished. These classes can be acquired online to streamline the process, due to the lack of deeper-level programming experience on the team.

After defining the classes, functions are used to connect and begin displaying our desired text on the LCD screen. After that, the only hurdle is receiving and handling the data. Utilizing the pins on the Raspberry Pi Pico and their connections to the voltmeter which we created, we can take in the voltage as a 16 bit quantity. We divide this by 2 to the 16th power and multiply it by 3.3 volts in order to put it in the scale of the voltmeter we have, and we can then deduce the voltage input at any time.

A difficulty in this method of detection lies in irregularities of data at instantaneous times. Even with measures to reduce noise like the feedback capacitor in the transimpedance amplifier circuit cannot prevent potentially irregular readings. We instituted an averaging function to cut away from those instantaneous irregularities. The logic essentially takes 8 readings within about a second (processing time notwithstanding) and sums them to then output the mean onto the LCD screen. We can more readily trust these outputs, as opposed to the previous instantaneous readings.

VII. CONCLUSION

The following systems outlined in this document come together to the final design of a Accessible Spectrometer for Water Impurity Detection. The end purpose of this device is to conveniently detect Chlorophyll A and Chlorophyll B concentrations in water samples by exploiting the Lambert-Beer Law wavelength-dependent absorption profiles of specific substances. We have successfully been able to measure variations between control and test samples within our device. This means that we have accomplished one of the design's initial goals of being able to detect chlorophyll impurities in a water sample. Further fine tuning in the optical designs to eliminate variables not mentioned in this document will be able to provide us with more consistent measurements. Currently, the exact concentrations of the chlorophyll impurities are unable to be consistently calculated due to minor variations in the optical design that occur when samples are removed/added to the system. This can be eliminated by investing in a more stable chassis and

ACKNOWLEDGEMENT

We would like to acknowledge the effort of our professors in the Departments of Electrical and Computer Engineering and of Optics and Photonics for their efforts in building our knowledge on these subjects thus far.

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Biographies

James Aurilio is a Photonic Science and Engineering (PSE) major, on track to graduate from the University of Central Florida with a Bachelors of Science in Photonic Science and Engineering (BSPSE) degree in May of 2022. He received a slot to perform in the United States Air Force as a Combat Systems Officer. After graduation, he will go to Naval Air Station Pensacola to begin his training after commissioning as a 2nd Lieutenant in the United States Air Force later in May.

James Aurilio (PSE)

James Brutus is a Photonic Science and Engineering (PSE) major, on track to graduate from the University of Central Florida with his Bachelors of Sciences in May of 2022. He will be commissioning as a Second Lieutenant in the Space Force with a Developmental Engineering career specialty code. He also received a slot to pursue a Master's of Sciences degree in Photonics Sciences at the University of Central Florida under a partnership with the Air Force Institute of Technology.

James Brutus (PSE)

Logan Farley is an Electrical Engineering (EEL) major student, on track to graduate from the University of Central Florida with a Bachelor's of Science in Electrical Engineering (BSEE) degree in May of 2022. He has received a job as a developmental engineer for the United States Air Force at Wright Patterson Air Force Base as a second lieutenant in the United States Air Force. He will commission as a brand new second lieutenant later in May 2022 and start at his new base after receiving his order later this year.

Logan Farley (EEL)