Color Acquisition Device (CAD)

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***Abstract*— We present a novel device for determining the reflectance or transmittance of different objects at three different discrete wavelengths and reporting them to the user with a wireless Bluetooth LCD. Using a 100m long polarization-maintaining silica fiber as a single-pass stimulated Raman scattering source when pumped by ~1.2kW peak-power, 5ns wide, 1064nmn wavelength laser pulses at a repetition rate of 20kHz, two wavelengths at 1120nm and 1178nm are generated (when polarization is not aligned to fast or slow fiber axes). These generated wavelengths and the pump acquire distinct temporal shapes whose linear combination makes up the exiting gaussian pulses that, with proper signal analysis and software tuning, are used to analyze and extract the spectral content of the target that is reported to the user; all is done without the need of additional laser cavities, diffractive optics, and by using a single high-speed detector.**

Keywords—optical fibers, silica glass, stimulated Raman scattering, spectroscopy, nonlinear optics

I. Introduction

Laser detection and ranging (LADAR) is a method of measuring distances by illuminating a target with laser light and collecting the reflection with a sensor. Devices and systems that take advantage of this ranging technique are capable of mapping entire scenes by measuring the total travel time of light and knowing its speed. Some potential applications of these technologies are archaeology, self-driving cars, and surveillance.

Conventional LADAR devices are limited to operating at a single wavelength, restricting their application to ranging, which comes with limitations. A single wavelength is enough for mapping and range estimation, but it might not be able to penetrate some obstructions or the resolution of the LADAR system might be limited (e.g. in a complex urban scene or jungle where a lot is going on); thus making it hard to distinguish objects in a scene. Detection capabilities can be further improved by introducing additional wavelengths into the system. These additional wavelengths could be capable of penetrating through some obstructions in addition to providing the user with multispectral measurements, thus improving the capabilities of a LADAR system by adding the ability to detect and identify objects based on their spectral signatures; especially when the system cannot make out the full object shape as with traditional LADAR [1].

Since making a LADAR system is very difficult and time consuming, we decided to try to design and make a spectrometer that takes advantage of the multispectral aspect. However, we decided to use an actual airborne LADAR laser to see if our device is capable of functioning with the faster repetition rates and the short pulse durations required. This made our project slightly more challenging, but very rewarding.

As with any engineering project, we established three key engineering specifications. First, make a laser system capable of emitting multiple wavelengths at once without using multiple cavities. Second, be able to use those wavelengths to characterize objects by measuring their wavelength-dependent transmittance (as a proof of concept) or reflectance without the need of additional diffractive optics and multiple detectors. Third, be able to provide the user with the measured transmittance or reflectance outputs for each wavelength after post-processing with a computer. All of these combined should take low cost, size, weight, and power (CSWaP) into consideration.

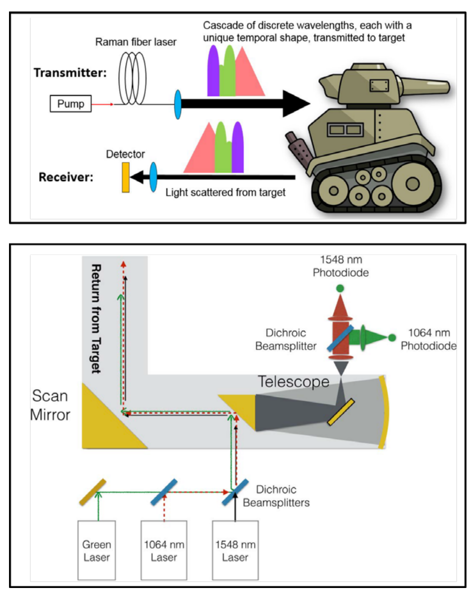

Fig. 1. Our current triple-wavelength fiber-laser design against current state-of -the-art dual-wavelength LiDAR system [1], [2].

For this, we decided to design, build, and prototype a one-of-a-kind single-pass Raman-based fiber-laser spectrometer, capable of emitting multiple wavelengths at once, that can be used to obtain transmittance and reflectance measurements by using only the time-domain and report them to the user with a Bluetooth-connected LCD. This gets rid of the need to introduce additional laser cavities, diffractive optics, multiple detectors, and wires typically used in commercial spectrometers and state-of-the-art multispectral LADAR systems. Thus, making this a revolutionizing low CSWaP system. Note that if implemented into a LADAR system, only reflectivity measurements are possible [2].

By pumping a silica glass polarization-maintaining single-mode (PM-SM) optical fiber with 5ns wide, ~1.2kW peak-power, and 1064nm wavelength pulses at a 20KHz repetition rate, two new Stokes wavelengths at 1120nm and 1178nm are generated and can be slightly tuned (or new ones can be added) depending on the input polarization. This occurs because of the increased interactions of the generated Stokes waves along the length of the fiber. A cascading effect results from this interaction, where the pump generates the first Stokes wave and this Stokes wave becomes the new pump for the second Stokes wave, and so on. This effect yields sets of frequencies ~13-14THz apart from each other that can easily be separated spatially by using a grating and characterized individually. Since these wavelengths have distinct features in the time domain, we refer to them as waveforms.

After spatially separating the waveforms in this manner, the system can be calibrated by using a high-bandwidth analog to digital converter (ADC), which in this case is a Tektronix CSA7404B oscilloscope, and a robust software program. Knowing that, due to conservation of energy, the gaussian pulse envelope coming out of the fiber is a linear combination of the residual pump and generated waveforms, the relative intensity of each wavelength can be extracted by knowing their position within the envelope and the small cross-contribution of neighboring waveforms that play a role on the sum. Hence reducing an otherwise complicated analysis, into a simple linear system of equations problem of three equations with three unknowns. Using this process to find the peak powers for each wavelength before and after being passed through or reflected from a target enables for the ratio to be taken, yielding the object-specific transmittance or reflectance, respectively.

This is then reported to the user by using an LCD coupled to a custom printed circuit board capable of sending and receiving data via Bluetooth (but will only be receiving data from the signal analysis software in this application). The custom PCB features an ATMEL ATmega328P-PU that is used on many Arduino boards such as the Arduino UNO rev 3, a Bluetooth module capable of 10 meters of free-space communication, and an 20x4 LCD that is easy to read and can output a significant amount of information. We also designed a small power supply that is included in the custom PCB microcontroller. This power supply gets its power from a 9 volt battery. The custom PCB was designed on Autodesk EAGLE using references from various sources online who have worked with the Arduino platform along with reference material from the Arduino company itself. All these components together ensure that the user will be able to access information about what our laser system is measuring while being mobile and not tethered to the post processor or a computer.

Machine learning for object classification based on measurements obtained with this device was a stretch goal that we investigated and tried to implement. K-nearest neighbor (KNN) being the method we looked into because of its ease of use and ability to analyze clusters of data to predict a specific outcome; in this case it was to predict a previously characterized object chosen at random.

II. Theory

A. Raman Signal Analysis

Stimulated Raman scattering (SRS) is an interesting nonlinear optical phenomenon. Unlike frequency conversion processes such as second harmonic generation, sum frequency generation, difference frequency generation, and four-wave mixing, SRS is nonparametric and non-phase-sensitive [3]. This means that it can easily be achieved in media where long interaction lengths are a possibility and power densities are high enough to make the material respond nonlinearly. Optical fibers are the ideal medium for this as they possess the ability to do this and withstand power densities up to $\sim 5GW \cdot cm^{-2}$ [4].

In the late 1970's, Leonard Cohen and Chinlon Lin reported a universal fiber-optic measurement system based on a near-IR fiber Raman laser [5]. There, they presented the following equation:

$$\frac{1}{2} \cdot \frac{GP_tL_t}{A} = 15, \tag{1}$$

where G is the peak Raman gain of $\sim 0.92 \times 10^{-11} cm/w$, P_t is the threshold pump power, L_t is the threshold length, and A is the mode area. Equation (1) showed reasonable agreement with experimental results and we used it to calculate the fiber length we would need when pumping with some pump power density. In our case, the $1/2$ was neglected because we were using a polarization-maintaining fiber and polarization scrambling could be ignored.

When using a high-power pulsed laser, of some center wavelength λ, the medium where light is traveling, in this case a silica glass PM-SM fiber, will respond nonlinearly and generate wavelengths shifted by some amount, Ω_i, from the pump. Since the Raman response of silica glass is in the order of a few hundred femtoseconds, as the pulse of wavelength λ evolves in time, the generated waveforms with wavelengths λ_i, will all be symmetrically spaced within the pulse and are all distinct (including λ). This means that the linear combination of the generated wavelengths will make up the pulses coming out of the medium [2]. A simple, useful, and elegant way of showing this was reported by Ausley, Keyser, and Martin with the following equation:

$$S(t, \lambda_i) = \sum_{i=0} P_i(t-\tau, \lambda_i)\, \kappa(\lambda_i). \tag{2}$$

In equation (2), $P_i(t-\tau, \lambda_i)$ is the power of the pump (when $i = 0$) or of any of the other wavelengths generated in the optical fiber. The time constant τ represents an arbitrary offset in time that the individual wavelength experience or that can be added during the analysis. Information pertaining to the atmospheric transmission, detector response, and distance to the target is all contained within κ.

Another name for $S(t)$ is the Raman pulse envelope, which has the same shape in time as the original pump pulse, but the different waveforms corresponding to wavelengths λ and λ_i are contained within it. Knowing the temporal shape and position (determined by τ) of all waveforms makes it possible to analyze all of the wavelengths in the time domain by using a single detector without any diffractive optics to separate the wavelengths in space (except for when the system is being calibrated). A straightforward way of doing this is through Kevin's method. Given some measured envelope, we may find the amplitude of each of the waveforms by assuming symmetry and solving the following matrix:

$$\begin{bmatrix} 1 & C_{S1,P} & C_{S2,P} \\ C_{p,S1} & 1 & C_{S2,S1} \\ C_{p,S2} & C_{S1,S2} & 1 \end{bmatrix} \cdot \begin{bmatrix} P_{peak} \\ S1_{peak} \\ S2_{peak} \end{bmatrix} = \begin{bmatrix} M1 \\ M2 \\ M3 \end{bmatrix}, \tag{3}$$

where P_{peak}, $S1_{peak}$, and $S2_{peak}$ are the amplitudes of the waveforms that must be solved for, $M1$, $M2$, and $M3$ are the amplitudes of the given envelope at the point in time where the known waveform peaks are located and the c-constants are the contributions of the neighboring waveform in the sum of the peaks, which is known after proper calibration. Note that we did not account for any dispersion effects but are absolutely necessary for actual fielding of the device.

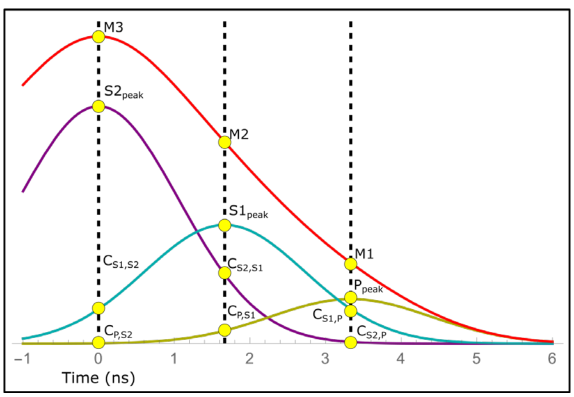

Fig. 2. Basic example of Kevin's method fone with the right-hand half of a gaussian pulse. Three waveforms make up the pulse that exits the Raman fiber (red), including the pump λ_0 (dark yellow), Stokes 1 λ_1 (dark cyan), and Stokes 2 λ_2 (dark purple). Yellow circles indicate the values that go into the left-hand side of matrix equation (3) and the peaks of P, $S1$, and $S2$ must be solved for. Note that symmetrical contribution from the left is not shown and in our case may be neglected.

Finally, to make this device actually characterize something via transmissivity or reflectivity, we apply very simple ratio relations. For an object's transmittance, we compute:

$$T = \frac{I}{I_0}, \tag{4}$$

where T is the transmittance, I is the intensity of light after it has been filtered, and I_0 is the original intensity. For reflectance, we compute:

$$R = \frac{J}{I_0}, \tag{5}$$

where R is the reflectance, J is the amount of light reflected from a target, and I_0 is the original amount of light (before target is placed or from some Lambertian diffusely reflective "base" target that is used to make measurements with respect to it). Note that for reflectance measurements, it is imperative to know the solid angle of the lens so that the exact amount of light that is going through it is accounted for. Also, another "tricky" aspect of reflectance is that some objects are more diffusely-reflecting while others are more specularly-reflecting; therefore, a way to account or measure this distinction should be implemented into the device.

B. Machine Learning and Object Classification

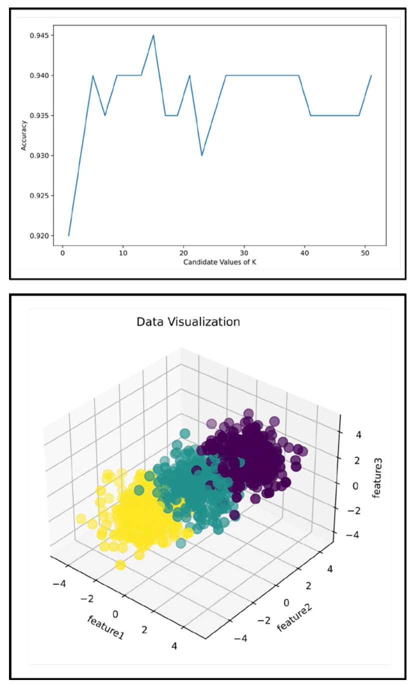

Fig. 3. Example of K-nearest neighbor. Measured feature 3-space (left) and K value optimization (right). For the machine learning algorithm to make an accurate classification and identification, different values of K should be used until optimization and highest accuracy is reached.

One of our stretch goals was object classification and identification. To do this, we require machine learning and hundreds of waveforms from a single object to train the machine learning algorithm. For this task, we proposed using KNN.

In KNN, the desired output depends on a set of features that in this case are the three wavelength that we decided to work with and that correspond to transmittance or reflectance. Simply put, KNN compares an unknown object that must be classified with points in this feature 3-space. Depending on where this object's measured wavelengths lie in the feature space, the algorithm will evaluate the points that lie nearest to what was measured from this unknown object. Based on the value of K, which is a positive integer that is typically small, the algorithm will compare the new unknown data with a K number of neighboring points and try to predict that the object is. Hence why previously measured data must be fed to the algorithm and it must be trained to do this.

III. Design

A. *Optical Design*

When characterizing the pump laser, it was found that the output was slightly outside the collimator specifications. The collimator was a combination of the Thorlabs SM1PM10 with GL10-C26 Polarizer (1064nm V-coating) and a Thorlabs F810APC-842, 842nm FC/APC collimation package, NA = 0.25, f = 36.18mm, AR coated 650nm – 1050nm. With this setup on, the following characteristics were measured: max average power of 1.2W (50Khz), PRF of 20KHz to 50KHz, pulse width of 3.0nsec (FWHM), beam size: 3.6mm (D4sigma), and a divergence of 0.36mr (D4sigma). These measurements, although not bad, were used to improve the pump and the overall performance of our system by using the F810APC-1064 FC/APC Collimation Package, NA = 0.25, f = 36.60mm, and the high power, 5mm, 1064nm, 1/2 waveplate Newport ISO-FRDY-05-1064-W isolator.

After ensuring that the pump worked as intended, the multispectral Raman laser itself was devised. First, a Thorlabs LPNIRB100-MP2 linear polarizer was put at the beginning and in the way of the pump beam as an additional power-control measure. Then, two silver mirrors were used to correctly align the laser into the AHWP10M-980 half-wave plate, that controls the polarization of the laser pulses, and the LMH-20X-1064 objective used to launch light into the PM-SM fiber.

On the output side of the silica fiber, we held the fiber with a brass chuck and a fiber holder. This was coupled to a C240TM-C, f=8.00mm, 0.50NA, mounted Geltech aspheric lens for proper collimation. This is where there is three paths for the laser: reflectivity target, blazed grating 0th order specular reflection, or space-separation for time-domain peak location.

Starting with the first, a target holder is put in the beam path. Opaque targets such as plywood, leaves (green or brown), and soil are put in the way of the beam to pick up their diffuse reflection by using a Newport KBX061 lens that focuses this light into a multimode fiber coupled to a Thorlabs DET08CFC, 5GhZ bandwidth, InGaAs high-speed detector. The second beam path requires that a $1\mu m$ reflective blazed grating be placed in a way that makes its 0th order of diffraction a reflection of the incoming laser beam. Then, an object (in this case neutral density and bandpass filters) is put in the way of the 0th order reflection so that its transmissivity may be picked up by a multimode fiber coupled to the same high-speed detector as before. Finally, the 1st order of diffraction from this grating is used to spatially separate each of the generated wavelengths so that they can be individually detected by three of the same Thorlabs high-speed detectors and be used to correctly calibrate the software

The signals from the detectors were sent to a Tektronix CSA7404B oscilloscope, which acted as our ADC converter, to then be post-processed by a computer with a Python program that we made.

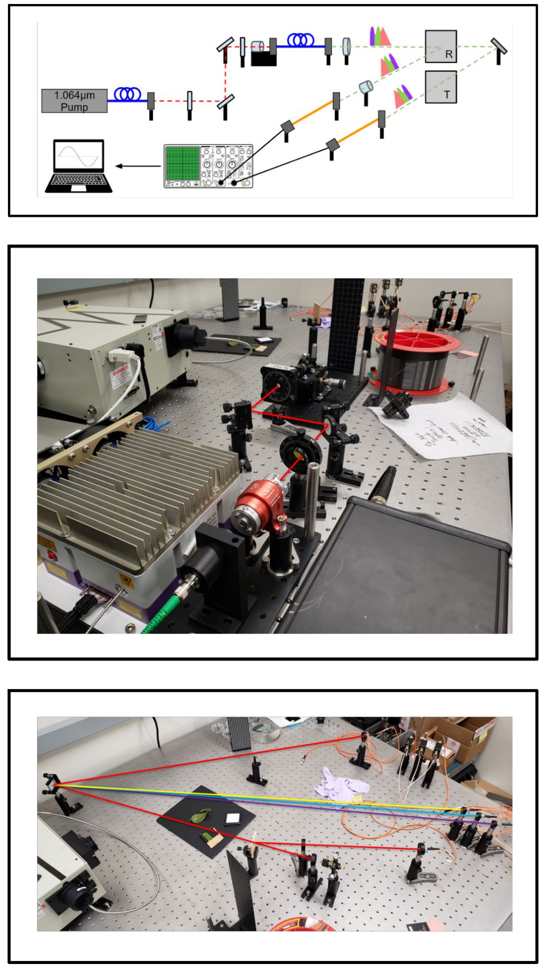

Fig. 4. Optical design schematic showing the layout of all of the optics and a reflective target represented with an R and a transmissive target represented with a T (top). Laser beam path from the pump to the half-wave plate; the coupling stage for focusing light into the fiber is located behind it (middle). Output setup showing the the three possible beam paths, red indicates Raman envelope, yellow, blue, and purple indicate the three wavelengths separate in space for calibration (not shown in the top schematic) (bottom). Plywood was in the way of the beam when picture was taken (bottom).

B. *Electrical Design*

The electrical design began with the concept of portability. Since this is an expensive and cumbersome laser system, the user should be able to easily identify objects from a remote-controlled device. With this, objects can be detected without needing to constantly stand directly with the laser system. Furthermore, it will be contained in a durable, small remote so that the user will not have to carry around an expensive computer to process the data on their person. Wireless Bluetooth communication provides advantages over Wi-Fi, notably that it does not need to also establish a proper internet connection.

Bluetooth was also chosen because of its simplicity to implement within the project and ease of use for the user to connect. This device would likely be utilized in locations where internet connections are weak or non-existent.

The Bluetooth HC-05 module was chosen for its various properties that make it ideal for programming and setting up. Since it is not a Bluetooth Low Energy (BLE), it can be operated from a mobile device as well as laptops or desktops. As a result, difficult calculations are performed with a computer (connected directly to the laser system), and this sends the data to the remote. Furthermore, the HC-05 module has connections for both transmitting and receiving data. While our purposes do not require sending data, future implementations could utilize this to operate the system remotely.

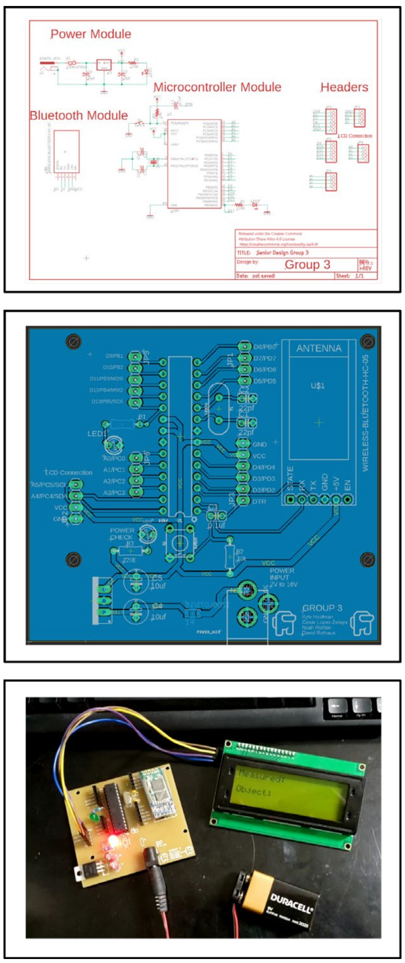

Fig. 5. Electrical design schematics showing the schematic (top), the board layout (middle) and the working system (bottom). This custom, pcb was made with the purpose of being a mobile remote that a user can see information about the object that is being analyzed by the laser and the computer software and was designed using AutoDesk EAGLE. In the board layout the blue represents the copper pour which is a ground plane. The board was also designed to be a one layer PCB. SparkFun libraries were used for most of the components in the schematic of the board.

Using AutoDesk EAGLE the first version of the PCB was designed in a twostep process which can be seen in the above pictures starting with the schematic. The library for all the components in the schematic was from SparkFun. The SparkFun library was used because of its large list of components with footprints that would be easily found online when selecting and procuring parts. The schematic was laid out in a compartmental way that is easy to read and edit with clear labels. The first version of the board was a simple design similar to an Arduino UNO, with a power module consisting of a fuse, voltage regulator, and power jack. The rest of the components include an ATMEL ATmega328p-pu processor, a socket, headers, reset switch, and a 16MHz crystal oscillator. The board was laid out in a way that only a single layer was required with a copper pour (in blue) which represents the ground plane. While this design worked as intended, many of the components had to be connected using jumper wires. Unfortunately, this was far too bulky and prone to disconnections during use, therefore the board needed to be re-designed for a version two. The second version of the board included a Bluetooth HC-05 module directly implemented onto the board, significantly reducing the size of the display. Furthermore, the voltage regulator was bent down to reduce the height of the board. To connect the 20x4 LCD, an I2C module was utilized to reduce the number of connections from 16 to 4, vastly reducing the overall size of the remote. This second version of the board was also implemented in a way that only required a single layer, which reduced complexity and cost.

A 16 MHz crystal oscillator was selected because of its accuracy and consistency, and was connected to two 22 pF capacitors in parallel. The two capacitors were selected based on the following formula

$$C_L = \frac{C_1 \cdot C_2}{C_1 + C_2}, \tag{6}$$

with C_L equaling 16 pF for our selected oscillator. A 5 pF buffer was chosen, thus 22 pF were selected. The power module was created by using two 10 µF capacitors, which smooth out the power from the battery or other potential power source. A fuse was used in the event the remote is being plugged into a larger power source that is prone to surges, though this will likely not ever be used. A 7805 voltage regulator was used since an output of 5 V is necessary, where our input is a 9 V battery. The power input can handle batteries with an output voltage between 7 V and 16 V, should a 9 V battery not be available. A reset pin on the microcontroller was connected via a 10 kΩ pull-up resistor. A switch can be pressed which will ground the pin, and resets the device. The last notable components are two LEDs, which were used as a way to see if the device is receiving power, and another for any additional purposes which is controlled by a digital pin on the ATMEGA328p-pu, the second LED could be used for a purpose such as troubleshooting. These were connected to the boards power system via a 220 Ω resistance. After the schematic and the board layout was finalized, an Electrical Rules Check and a Design Rules check from SparkFun were used to make sure there were no errors in the design of the schematic and board.

Once designing the PCB was finalized part selection was the next step. Amazon was used for the embedded parts such as the

20x4 LCD display with I2C module, and the HC-05 Bluetooth module, while the smaller parts such as the ATMEGA328p-pu and various resisters capacitors was procured from Digikey. The PCB itself was procured from JLCPCB by inputting the Gerber files from EAGLE into their website so that the PCB could be manufactured to our design specifications. For the assembly of the PCB with the components we used a soldering iron and soldering wire. Once soldering was complete and the board was tested for functionality, the lingering flux was removed by application of 90% isopropyl alcohol with a brush.

C. *Software*

In order to understand the code utilized throughout the system, it is important to distinguish the three different files within the entire project and understand their unique purposes. In order to give an intuitive understanding of the code and how it processes data, we present the files in the order that they should be run. The first is "ColorFinder2", the second is "KNN_ColorFinder", and the final code is "PCBCommunication". These were created in Python since they contain pre-made libraries that incorporate functions that are extremely useful for our signal analysis.

"ColorFinder2" is labeled with a 2, as this is the second version of this project. This is the main bulk of the code and contains over 500 lines of code related to processing the files from the oscilloscope. It uses multiple libraries found online: pandas, for reading and working with the large CSVs (comma separated values) that are output from the oscilloscope, matplotlib for plotting data for visualization and debugging, and numpy for mathematical calculations with this data. The input for this file is data from the oscilloscope, and the transmittances or reflectances of the object are output. The user is able to choose what graphs are desired, or any other values (such as graphs, or important voltages), through the arguments when calling the function.

The file begins by reading and merging the files using pandas to create a dataframe of the data. After this, it shifts the data automatically, in order to center it. There is an option for the user to shift the data manually, should they choose to do so. The next function performs signal analysis on the data that has been merged in the desired manner. To do so, it uses the method described earlier in the theory section of this report, using matrices to calculate the peak values of the individual wavelengths using the calibrated data of the individual wavelengths. The user can decide whether they want to find the transmittance or reflectance. Both functions use a similar method to find these values. This will then send data to the other functions.

KNN_ColorFinder integrates our stretch goal of creating a K-nearest neighbor algorithm that will use past data to train a system to interpret objects placed in front of it. It begins by taking a folder of many CSVs from the oscilloscope (of a single object) and running them through the ColorFinder2 file until it has processed every single file within the folder. Currently, it is created to interpret transmissivity data. As such, the transmittances output from ColorFinder2 are stored into a large array, with a new row for each of the files processed. With this new array, all of the data needed to train the system can be stored in a single CSV as opposed to an entire folder of them. This saves storage on the hard drive and computation time in the future, when actually running the algorithm to decide what the object is.

The transmittances are also sent to the PCBCommunication file. The purpose of this file is to send the data over Bluetooth and communicate with the remote LCD that we have created. It begins by receiving the variables from the ColorFinder and formatting them in a way that can be displayed onto the LCD. It then begins a loop that will send flags to the microcontroller. When the microcontroller is ready to receive data, it will send a 1 to the system. This way the system will know to send data to the display through Bluetooth. To do so, this imports the serial and time libraries to create a path to send data and a way to keep time to avoid conflicts when sending or receiving data, respectively.

The microcontroller itself is programmed using Arduino IDE. This is because of its ease of use and pre-made functions that will allow the Bluetooth to work with few issues. This code begins by initializing the Bluetooth and LCD. Once this is done, it puts itself into a loop, constantly sending out a signal when it is ready to receive data. In the time that it is not receiving data, it instead prints to the LCD screen. Currently, this prints a line saying "measurements" for the transmittances and "object" where it prints the object being detected.

The ATMEGA328p-pu on the PCB was programmed by removing it from the socket and placing it in an Arduino UNO board to be programmed via USB. The reason for this method of programming is because the TX and the RX pins are permanently being used on the ATMEGA328p-pu which causes the processor to be non-programmable through serial means. Using the Arduino IDE which is a variation of the C programming language the ATMEGA328p-pu can control both the 20x4 LCD and the Bluetooth module.

The software flow in the Arduino IDE is as follows; libraries are included for serial communication for the LCD display, the HC-05 Bluetooth module and the I2C module attached to the LCD. Then in the set-up the LCD, the serial connection, and the buffer that holds the serial data over Bluetooth are initialized. Then in a loop using the cursor function of the LCD library along with if statements the remote sends a flag through Bluetooth that tells the computer that the device is ready to read new serial information. Once serial data is sent byte by byte for the first row of the LCD is complete the device will move to the next line and begin the same process but with a different flag. Each time when sending data and receiving data there is a short delay added so that the ATMEGA328p-pu can process any new serial data. Once this process is completed for all four rows of the LCD the process starts over. Also included in the Arduino IDE code is a counter that resets the device after every three loops so to reduce errors.

IV. Results and Discussion

To begin, we consider the current device to be a success. Not only is it capable of measuring transmittance and reflectance on the fly, but it is also capable of quickly displaying those measurements to the user remotely via Bluetooth. Additionally, the generation of multiple wavelengths without the use of additional cavities ad its wavelength tunability (by changing the fiber input polarization) makes it a more applicable and robust device in practice. An important thing to note is that to try to keep it as low CSWaP as possible, we opted to use the least amount of expensive optics and cut corners whenever we could. Since this was not an experiment, importance was not placed on setup perfection, but on its ease to build and use.

The maximum coupling efficiency into the PM-SM fiber was of ~19%, mostly because the spot size of the microscope objective was $\sim 2.5\mu m$ compared to the $\sim 6.6\mu m$ mode-field diameter of the single-mode fiber. This actually indirectly helped us because with the addition of some polarization scrambling, we managed to get a nice three-wavelength output at 1064nm, 1120nm, and 1178nm with pump peak powers of ~1.2kW. Interestingly, when aligning the input polarization with the fast or slow axes of the fiber, some wavelengths spanning ~1030-1500nm were detected by the Ando AQ6315A Optical Spectrum Analyzer. Spectral broadening caused by the broad Raman gain and four-wave mixing was also a bit of a concern so proper polarization tuning, alignment, and pump powers were used to try to obtain the narrowest spectral emission lines possible. Note that despite the lines being broad, the shape in time of a line, regardless of it being measured at the short or long wavelength end, had the same temporal shape. To avoid any issues with this, however, we chose to use the most intense wavelength of the "chunky" emission lines.

On the output side of the Raman fiber, we originally proposed building the prototype setup to detect and record the temporal shape of the Raman waveforms. Then, we were going to dismantle that and build setup dedicated to measuring reflectance only. However, as the blazed grating was placed far away to sufficiently separate the generated wavelengths spatially, we decided to take advantage of the 0^{th} order for measuring transmittance like a normal spectrometer, using the 1^{st} order to record the waveforms and make sure they were stable, and we decided to place a stage in the way of the laser beam (between the fiber output and grating) to place an opaque object in the way and measure its reflectance. This fortunate decision expanded the capabilities of our device and made it applicable not only to multispectral LADAR by being capable of obtaining reflectivity measurements, but for spectroscopy by being able of obtaining transmissivity measurements as well.

One major drawback from the output setup was the fact that the detectors could not properly detect light at higher peak powers (>75mW). Originally, we were using aspheric lenses to focus light into the detector-coupled multimode fibers, but this caused one of our detectors to burn because of the high peak powers still present in the output setup. For this reason, we had to send the collimated beam straight into the fiber, sacrificing efficiency for the life of the detectors. Regardless of this decision, measurements taken with our device still agreed very well with what is reported by the manufacturer of the filters and objects in literature.

While the electronics are compact and output what we expected, there are certainly improvements that could be made. One of the most notable is the size of the PCB. Currently, it is a larger height, width, and length than is certainly necessary for the product. This could be shrunk down through either reducing the overall footprint of the printed circuit board (whether through a multi-layer design or rearranging the components) and using more surface-mounted components. From a software perspective, the device still could use some work on fine-tuning the timings of the system. There are still some issues where the LCD will temporarily display the wrong data. Though it corrects itself, this is still not an ideal behavior when using the remote. Lastly, the Bluetooth display would be much more usable contained inside a box, as this would make it much more portable, and less difficult to use for those who are not acquainted with the system.

Additionally, problems encountered along the way for the electronic component of the project included the mismatching of the TX and RX pins in the board layout, this was solved by using insulated wires and switching them in the soldering process. Another problem encountered was programming ATMEGA328p-pu serially. This could have been solved by using software to allocate the TX and RX pins to any of the digital pins on the board because when the TX and RX pins are in use the ATMEGA is not programmable. An improvement to the power system could be the use of a diode so that current only flows in the direction that was planned for the design. Other improvements to the programming of the board would be to reduce delays in the Arduino IDE code so that the user receives information from the computer faster.

To test out the accuracy of our software and performance of our device, we used the transmission portion to our advantage. We had three filters available to us, a 1mm-thick Edmund NG3 filter, a 2mm-thick OD1.7 filter, and an Edmund RG9 longpass filer. In a span of a few minutes, we recorded the pulse envelope coming out of the Raman PM-SM fiber, then placed each of the three filters on the way and recorded the filtered envelope. These envelopes were then scanned and post-processed by our Python code by using Kevin's method. Shortly after, the Python code got a result and sent it to the LCD, which reported to us the results. Very good and reasonable agreement was found between our measurements and what was reported by Edmund Optics. Another small drawback is the slight power fluctuations of each laser pulse. This adds some randomness to the measurements that we obtain, with a maximum error in transmittance and reflectance of about $\pm 1\%$, i.e. a filter might have a transmittance of 45% for 1064nm wavelength, but because of slight and fast power fluctuations we might obtain a transmittance anywhere between 44-46%, which is acceptable. For completeness, the following table lists transmittance results that we got for each of the filters vs what is reported by Edmunds (or OD labeled on the filter). Note that, from left to right, the numbers correspond to wavelength of 1064nm, 1120nm, and 1178nm.

TABLE I. MEASURED TRANSMITTANCES COMPARED TO MANUFACTURER SPECIFICATIONS

Filter Type	*Measured*	*Expected*
NG3	[21.1, 20.9, 21]	[20, 20, 22]
RG9	[47.2, 2.9, 3.5]	[46, 1, 0]
OD1.7	[1.6, 1.7, 2.1]	[1.9, 1.9, 1.9]

Fig. 6. LCD displaying Bluetooth-sent measurements obtained from the bandpass filter on the fly.

One of the biggest challenges we faced while working on this project was integrating the optics with the electronics. However, with high-speed detectors, the oscilloscope, a laptop, and Bluetooth communication, it was possible to easily integrate everything together. One last issue on the integration side was the lack of an easy way to communicate to the oscilloscope while it was directly connected to the computer. We attempted to use a GPIB-to-USB cable but no matter if we used MATLAB, Python, or TekVISA, it was not possible to directly connect to the oscilloscope. Therefore, when captured the waveforms, they were sent to the computer with a USB drive. Other than that, the device gave accurate measurements in a streamlined fashion from start (the target) to end (the LCD).

In conclusion, the device works as intended and upon measuring the transmittance or reflectance from an object, results are sent via Bluetooth to the LCD and reported to the user. Some slight variations in the measurement occur due to rounding and slight power fluctuations between laser pulses. Unfortunately, we were not able to meet our stretch goal, but are in the process of finishing it since it requires a significant amount of samples and training. Aside from that, the optics and electronics work phenomenally and were successfully integrated to make a novel state-of-the-art time-domain spectrometer.

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