Low-Cost Integrated Spectrometer

Design Document Check

Group: 18 – Lukas Janavicius, Drew Ingram, and Stephen Gioja

NetIds: janavic2, andrewi2, and sgioja2

TA: Charles Ross

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1 Introduction

1.1 Objective

For three centuries, optical spectrometers have played instrumental roles in advancing nearly all branches of science, from discovering new elements, determining the composition of stars, or even identifying and characterization of Two-Dimensional materials [1, 2, 3]. Given the technology's maturity, modern-day spectrometers have evolved since their initial conception, collecting and quantifying their data for instant analysis. However, budget digital spectrometers, including their required software, start at over $1000 [4]. This cost barrier effectively limits spectrometry techniques to controlled laboratory environments in Universities and other research institutions.

We aim to bring the cost of the digital optical spectrometer, lowering the barrier of entry and extending the applications of spectrometry. A spectrometer's cost lies in its expensive optics and dedicated high-frequency data collection hardware. Our proposed solution is to eliminate costly optical components by integrating an optical circuit in acrylic plastic and collecting the diffracted light using a linear CCD image sensor driven by a low-cost microcontroller.

1.2 Background

Integrated Photonic Spectrometers (IPSs) are a well-studied subject, fabricated in various materials and geometries; however, such literature presents narrow and novel applications of the IPS like broadband single-photon spectrometers [5, 6, 7]. Additionally, several open-source projects demonstrate digital spectrometers built with the Arduino framework but are limited in that capturing a single data frame takes 4 seconds over the 8-bit microcontroller's 115.2 Kbaud USB-UART connection [8].

1.3 High-Level Requirements

- The spectrometer's optics should be capable of resolving the plasma emission spectra of common gasses.
- The spectrometer must be capable of live plotting and capturing data.
- The cost of the spectrometer should be below $50.

2 Design

The spectrometer design in Figure 1 requires three primary modules to fulfill the above requirements. The photonics demodulate light inbound through a coupled optical fiber, as in Figure 2 and the outbound light is coupled into waveguides carrying a given spectral band. By using a three-dollar microcontroller, the ESP32, we satisfy the remaining requirements, as it overcomes the communication bottleneck of the Arduino's USB-UART connection through WiFi.

Additionally, with its two 240 MHz cores, the tasks of data acquisition and serving data to the user are split amongst the cores.

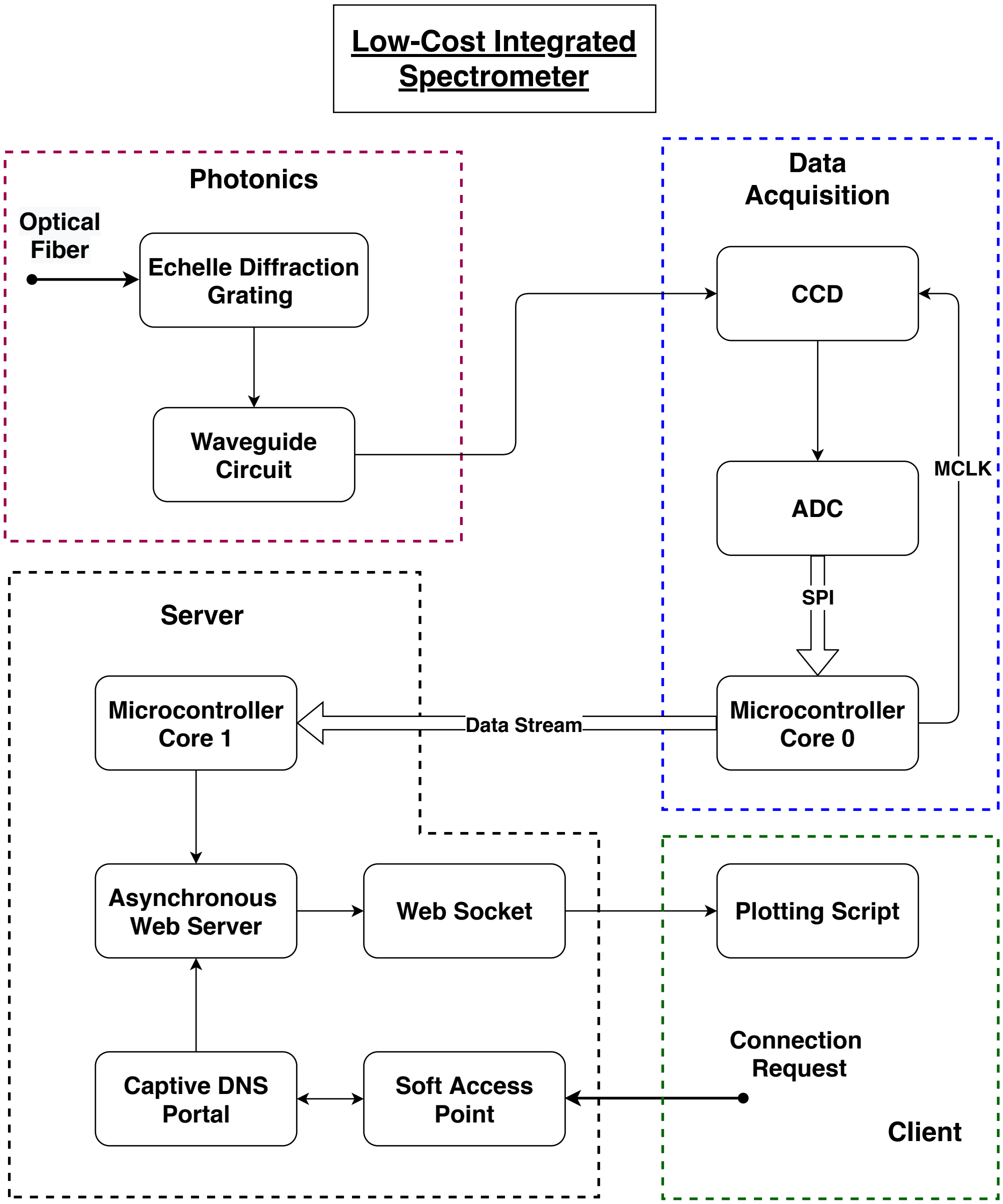

Figure 1. High-Level Block Diagram

2.1 Photonics

2.1.1 Concave Blazed Diffraction Grating

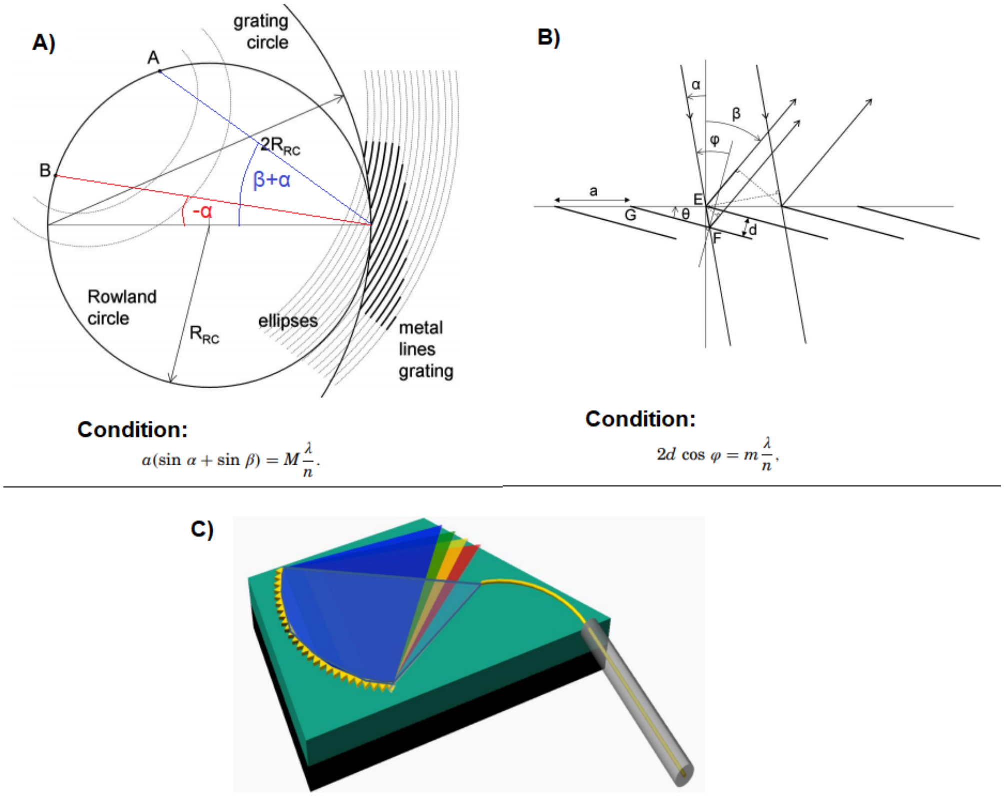

Figure 2. Integrated Spectrometer geometrical constraints from Pottier Ma et al. [6]. Subfigure A shows the general diffraction condition for a Rowland defined grating. Subfigure B shows the second, Bragg, diffraction condition of the elliptical grating. Subfigure C shows the device layout, the combined diffraction condition ensures only one output order [6, 9]

Different wavelengths of light will need to be physically separated. We plan to accomplish this by using an Echelle grating, as in Figure 2. Our design's broad-band capabilities demand a larger feature size than that of Figure 2, as detailed by R. Lycett et al. [10].

Requirement	**Verification**
Must diffract light within the range of 400-800 nm	(a) Place grating inside nanolab's quantum efficiency (QE) measurement system, between the Monochromator and CCD. (b) Sweep input wavelengths across the specified range, record the output diffraction order's position on the CCD as a function of wavelength. (c) Ensure our grating geometry supports a single high-order diffraction order, and that the output range falls within the detector length.

2.1.2 Waveguides

Waveguides act as the input and output to our photonic circuit, coupling the inbound optical fiber and the outbound spectrum. Since our design does not have integrated photodetectors, we must couple our waveguides to the CCD. Optical epoxy will couple the two materials.

Requirement: Must have atleast 48 output channels (Demonstrated in [6]).

2.2 Data Acquisition

2.2.1 CCD

Detects and measures the intensity of light on each pixel. The array of pixels allows us to resolve the output spectrum spatially. The CCD integrates the output spectrum with time, to prevent overexposure, it must be refreshed at a high rate, 1-2 MSPS. We propose using the TCD1103GF from Toshiba for its standard interface, low-cost, and 3.3V compatibility.

Requirement: Must drive the MCLK at 2-4 MHz.

2.2.2 ADC

The The ADC converts the CCD's analog readings to digital data for the ESP32. To match the CCD's speed the ADC must be compatible with the ESP's fastest serial communication standard SPI, and offer atleast 2 MSPS.

Requirement: Must sample at a rate of 1-2 MSPS.

2.2.3 Microcontroller Core 0

At a high level, the ESP32 SOC is configured with two tasks. Initially, we configure the platform's 16 peripheral timers, capable of a maximum of 40 MHz, to generate the necessary clock signals signal. Then, the task of monitoring the board hardware communicates with the ADC over SPI. Incoming data is streamed to the second core, which hosts an asynchronous web server.

Requirements	**Verification**
1. Must generate multiple 1-4 MHz clock signals for driving the CCD 2. SPI communication must support atleast 10 full 1500-pixel frames each second (30kbps)	1. (a) Configure the ESP to PWM 0-40 MHz on all clock related GPIO. (b) Confirm all clock pins can output atleast their respective maximum frequencies with an oscilloscope. 2. (a) Establish SPI communication with the ADC (b) The data rate out of the CCD must be the same as the ADC, 1-2 MSPS.

2.3 Server

The server will comprise an ESP32 hosting a network access point where the intended user can connect and log on to view their data in a web browser. The implementation of the server is beyond the scope of this class; however, the general requirements of each components are listed below.

2.3.1 Microcontroller Core 1

This Microcontroller asynchronously communicates to its WiFi IC and the other core. Additionally it hosts our web server with a complementary file-system.
Requirement: Cannot bottleneck the 10 frames-per-second required above.

2.3.2 Asynchronous Web Server

Requirement: Must serve the plotting script, and establish a websocket connection.

2.3.3 Web Socket

Requirement: Must connect to the user's plotting script and stream the data atleast 30kbps.

2.3.4 Captive DNS Portal

Requirement: Must immediately forward anyone connecting to our network to a webpage with our plotting script.

2.4 Soft Access Point

Requirement: Must allow users to connect by joining the WiFi network.

2.4.1 Plotting Script

Requirement: Defines a set of API functions which receive data from the microcontroller and forward them to a JavaScript plotting API [11].

2.5 Risk Analysis

The most challenging component to design will likely be the waveguide circuit. The waveguides will need to be placed very precisely in order to place each frequency of light on the appropriate pixel of the CCD. The density of the waveguides will be an important design parameter. More densely packed waveguides will allow for greater spectral resolution, but packing them too closely could result in interference and coupled-mode effects. FDTD analysis will be needed to optimize the waveguide design.

The waveguides also provide a challenge for the fabrication process; they must minimize losses, and couple to the CCD. This requirement implies aligning the waveguides to the CCD, and may lead to losses in our signal. However, as discussed by Y. Wang et al., we may not need to include waveguides as the Echelle grating disperses a continuous spectrum [9]. We have already reached out for consultation on this subject, but must decide quickly

3 Physical Design

The physical design of the spectrometer isolates the light sensitive hardware from the environment. Additionally, the optical feedthrough allows our spectrometer to connect to external optical fibers and instruments. The photonics are located off-center to allow for the ESP chip and its accompanying electronics. Also shown is the photonic slab mounted to the CCD.

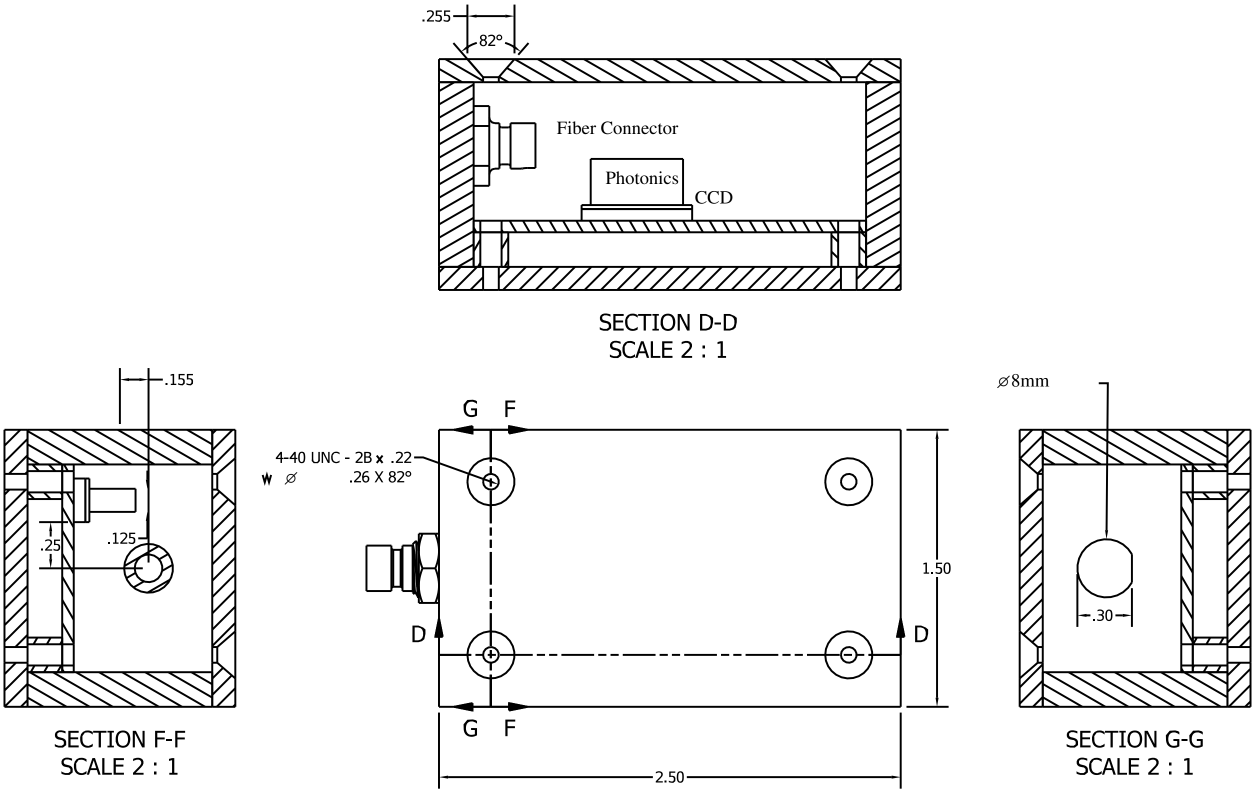

Figure 3. Integrated Spectrometer on Silicon [5].

4 Cost and Schedule

4.1 Cost Analysis

4.2 Schedule

5 Safety and Ethics

In the ACM Code of Conduct section 3.1 we see the main point of designing a new or enhanced device is should be to improve the lives of people [12]. This is our main goal which is reached by decreasing the cost of a spectrometer and therefore increasing the ability for people to obtain one.

Data from our device could potentially be used in scientific research and other sensitive applications. The user's data must remain private to the intended users [12]. Our device will host a private network access point. Unauthorized users could potentially log in and access someone's data or cause data loss. We will mitigate these issues by presenting the users with a standard network login using password protection.

While developing we must respect the works of others, which includes citing our sources and not claiming the works of others as our own seen in section 1.5 of the ACM Code of Ethics [12]. For some individuals and students it's difficult to not fall into laziness and not put a complete effort into something. We must resist that temptation and keep each other accountable to high quality workmanship [12]. Section 2.4 of the ACM Code discusses giving/receiving feedback. We must listen to the feedback from our instructors and TA's and consider it in our design.

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