High Resolution Multi-grating Spectrometer Controlled by an Arduino

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Abstract—We present the design for a high resolution triple-grating Czerny-Turner spectrometer for visible and telecom wavelengths, together with results of optical simulations using ZEMAX. Results from the simulations show that one of the most important factors affecting spectral resolution is the focal length of mirrors. Increasing the focal length allows for a greater degree of spatial dispersion of light diffracted from the gratings and also reduces optical aberrations. Radiation of wavelengths around 1550 nm are shown to have very noticeable aberrations in certain designs, evident by a large degree of smudging. Using parabolic mirrors instead of spherical mirrors is demonstrated to have a negligible effect when compared with increasing focal length. The optical simulations and preliminary testing of mechanical components show that it is possible to build a cost effective high resolution Czerny-Turner spectrometer using off the shelf components.

Index Terms— optical spectrometer, Arduino

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I. INTRODUCTION

Optical spectrometry is a process of analyzing the spectrum of light. It has a broad range of applications in areas such as astronomy, chemistry, and photonics. For example, Raman spectrometry may be used to identify the presence of certain molecules in an unknown sample, and Rayleigh scattering spectroscopy may be used to investigate the properties of an individual single walled carbon nanotube [1][2]. High-resolution spectroscopy capable of resolving spectral features spaced by less than ~10pm is in particular extremely useful for characterizing the spectral properties of solid state quantum emitters, such as self-assembled quantum dots, and semiconductor micro-cavities and photonic-crystal nano-cavities with high Q-factors[3][4].

Here we present the design for a high-resolution Czerny-Turner spectrometer with a focal length as long as 1.5m and three diffraction gratings[5]. While such spectrometers are currently available on the market, they are manufactured in very small volumes, which results in prices exceeding $100k.

A spectrometer generally consists of a monochromator, which separates the wavelengths of the incident light into different propagation directions, and of a calibrated one- or two-dimensional photodetector, that detects the relative intensities of light at each wavelength. The monochromator most often utilizes a diffraction grating with adjustable tilt, while the detector is usually a high-sensitivity CCD or CMOS camera for visible light spectrometers and InGaAs diode array for telecom wavelengths.

In a Czerny-Turner monochromator/ spectrometer, the input light is focused through a narrow slit, then collimated by a concave mirror with a focal length f, after which it propagates for a distance f where it hits a diffraction grating. Here, light of different wavelengths is reflected under different angles and, after traveling for a distance f, it is refocused onto the detector with another concave mirror with focal length f.

Our spectrometer was not fully built since many critical optical components had lead times of several months and would not arrive while Karl was still present at the University of Waterloo. However, thorough optical simulations predicting the capabilities of the instrument were performed using ZEMAX. Additionally, a prototype of a two-axial rotating turret allowing automated swap between the deployed diffraction gratings, which was called the TRISPEC, was built and is reported here.

II. Mechanical Design

Mechanical devices such as the TRISPEC, camera holder, mirror holders for 4”-diameter concave mirrors with 50cm focal length, and periscope were custom machined.

The acronym TRISPEC comes from TRIple Turret SPECtrometer, and refers to the target design feature that will allow the user to switch between active diffraction gratings. The ability to select which grating is used is important since each grating has a different number of groves/mm, resulting in different degrees of spatial dispersion of light. Therefore, the bandwidth of light which falls on the detector can be controlled by changing the diffraction grating. This allows the user to be able to select between examining a broad spectrum of light, and progressively select narrower bands of light for more accurate inspection of a particular part of the spectrum.

The simplest design for a triple turret would be to have, for example, one diffraction grating positioned on each of three faces of a triangle and this is in fact used in some of the commercially available spectrometers, such as Acton SP-2750 from Princeton Instruments. Switching a grating is then be a matter of rotating the triangle by 120°. A problem with this design, however, is that any further angular adjustment (to focus in on a spectral region) would have an axis of rotation which is not about the face of the grating. This causes the grating the partially move out of the incident light beam for more extreme tilt angles, which in turn limits the efficiency and wavelength range of the grating.

The TRISPEC design presented here solves this problem by using two axes of rotation. One is for selecting gratings and the other is for fine angular adjustments of the selected grating. A picture and schematic of the TRISPEC are shown in figures 1 and 2. The Parker rotation stage, Kohzu rotation stage, servo motors, and motor control were purchased online. All other materials were custom machined using 6061 aluminum in the student machine shop at the University of Waterloo. The mode of operation of the TRISPEC is as follows. For fine angular adjustments of a chosen grating the Parker stage is controlled. This is done with an STM-200 Stepper Motor, which provides more torque but also requires more current than the NEMA-17. To swap gratings, the Kohzu stage is controlled with the NEMA-17 motor. Both motors are controlled by an Arduino Uno and an Adafruit Motor shield. The motor shield is used since the amount of current outputted by the Arduino is not enough to power the motors. Connecting an external DC power supply to the motor shield permits higher power control of the servo motors, as well as control with useful waveforms resulting in microstepping and double coil steps. Using the Motorshield with 1.2 A and 8V is enough to operate the TRISPEC. How the TRISPEC fits in to the entire design of the spectrometer can be seen in Fig. 8.

Another important mechanical part of the spectrometer is the Periscope. In many optics labs, the beam height above optics table is kept at ~10 cm, as this provides a good compromise between mechanical stability of the beam steering components and convenience for manual alignment. However, given the large are gratings dictated by the long-focal length of the spectrometer and the use of two rotation stages for the grating turret, the resulting optical axis of the instrument is at roughly 17 cm. Therefore, a device is needed to raise the input beam from the optics table. The design for the Periscope is shown in figure 3. A parabolic mirror is chosen over a plane mirror so that the periscope may be used to raise the optical axis as well as focus the input light with minimized chromatic and spherical aberration. Adjustment rods and an XY adjuster are used since they allow for fine positioning of the parabolic mirror so that light very precisely passes through the entrance slits of the spectrometer.

III. ZEMAX SIMULATIONS

In addition to prototyping several devices necessary to construct the spectrometer, thorough simulations using Zemax Optic Studio were performed to assess the effectiveness of various design decisions. Decisions include choosing parabolic or spherical mirrors, the number of groves/mm of a diffraction grating, the focal length of mirrors, and the geometry of the components (i.e., the spacing between mirrors and TRISPEC, entrance slit and mirrors, etc).

Figures 4-7 summarize the results from the ZEMAX simulations. Figures 4 and 5 were generated using 75 mm diameter, 500 mm focal length silver coated spherical mirrors, a 1” diameter 30 mm focal length achromatic doublet, and a 4 mm initial collimated waist of light. The spectrometer was designed in sequential mode in ZEMAX. This allows for fast and precise positioning of optical elements. However, only one wavelength of light may be analyzed at a time in sequential mode, so the whole design was converted to non-sequential mode for multi-wavelength analysis. In non-sequential mode, the spectral resolution can be more effectively studied since comparing two wavelengths side by side allows one to see the effects of optical aberrations and dispersion due to different gratings more clearly. Figures 5 and 7 show graphically what the signal processing software to determine intensity of a certain wavelength would do. The graphs show the sum of the irradiance along a column of pixels. This is useful since in practice wavelength is determined by which column of pixels light is incident upon. If the two blue spikes are clearly spatially separated, then that is an indication that there exists distinct spectral resolution between the two wavelengths. How symmetrical the two peaks are indicate to what extent optical aberrations are present. The simulations show that a high degree of smudging results from using long wavelength light (~1550 nm wavelength) with diffraction gratings of 1200 groves/mm or higher. Intuitively, one might expect the greater amount of spatial dispersion resulting at longer wavelengths to positively contribute more to spectral resolution than any negative side effects such as aberrations would. However, the increase in full width 1/10th maximum cancels out the positive effects that greater dispersion would have on spectral resolution.

Full width 1/10th maximum is a measure of how horizontally concentrated light energy is on the detector. It is the spatial distance of the irradiance going from 10% of its maximal value, to its maximal value, and back down to 10% of its maximal value along a horizontal axis. The full width 1/10th maximum is relatively large for 1550 nm wavelength light and a 1200 groves/mm grating. Therefore, this combination of wavelength and gratings should be avoided. An important conclusion from these simulations is that full width 1/10 th maximum is mainly a function of wavelength and not number of lines/mm of the diffraction grating. For example, the full width 1/10th maximum does not change significantly when using either 1200 or 1800 lines/mm. However, prohibitively large full width 1/10th maximum occurs when using ~1500 nm light. One might expect that with a higher rules/mm diffraction grating more aberrations (such as smudging) would occur since light is dispersed at greater angles. This effect is noticeable but is not nearly as dominant as the effects of wavelength are. Figures 6 and 7 show the effects of focal length on spectral resolution. Clearly, with greater focal length there is more distinct separation of wavelengths. All of the figures show light of 852 and 852.01 nm wavelength. Figure 7 shows that with greater focal length asymmetries in the light hitting the detector are reduced. This is because a smaller tilt of the diffraction grating is needed with higher focal lengths. Less tilt means the light is better able to remain collimated. Figures 6 and 7 also compare the effects of using a parabolic as opposed to spherical mirror. The reduction of spherical aberrations resulting from using parabolic mirrors is negligible, since greater focal lengths have a much more dominant effect in improving spectral resolution.

IV. SUMMARY AND CONCLUSION

A high spectral resolution spectrometer was designed and several main components of it were prototyped. Complete construction of the spectrometer was not possible since critical optical components would not arrive in time. However, thorough ZEMAX simulations were performed for the high resolution spectrometer as well as multiple other configurations. The ZEMAX simulations show that spectral resolution is directly proportional to focal length. Additionally, optical aberrations are reduced with shorter wavelengths of light (850 nm vs 1550 nm). One part of the spectrometer which was built is the TRISPEC. This device allows the user to select one of three diffraction gratings to be active, as well as finely adjust the angular position of the selected grating about the face of the grating. This device is controlled by two servo motors, an Arduino Uno, and an Adafruit motor shield. Looking forward, decisions must be made as to whether a composite grating system as opposed to a single grating on each face of the TRISPEC will be used. This decision would affect how the TRISPEC is built. The presented model was built to allow a composite grating to be attached. This is so that off the shelf gratings can be used and also to make the design more affordable. In order to build a spectrometer with the highest spectral resolution, long focal lengths such as 152 cm (60”) should be used. This would also reduce optical aberrations. Ideally, parabolic mirrors would also be used, but the effects of focal length are much more dominant than the type of curvature. With these design decisions in mind, a cost efficient spectrometer which minimizes aberrations and provides high spectral resolution can be built.

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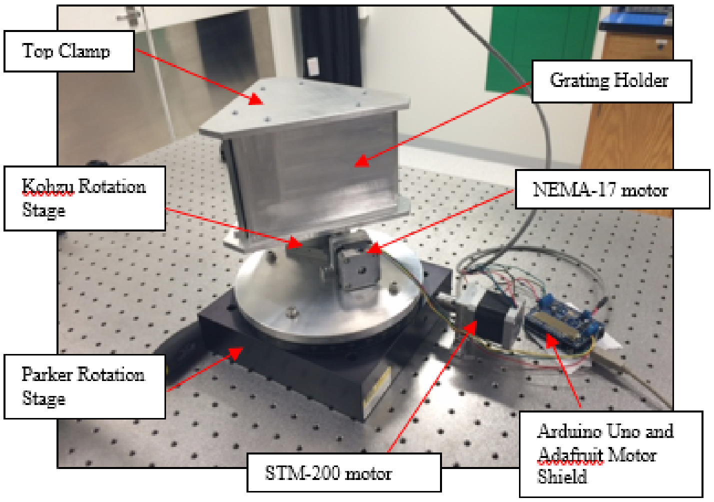


Fig. 1. TRISPEC connected to an Arduino control unit. Diffraction gratings which would be inserted on the device are not shown.

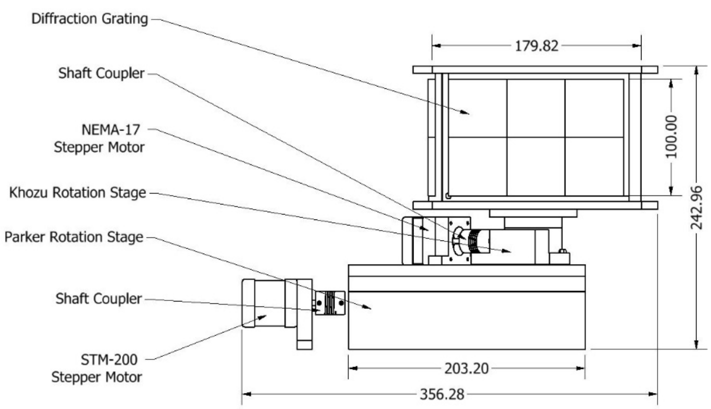


Fig. 2. A drawing of TRISPEC generated in Inventor. All units are mm.

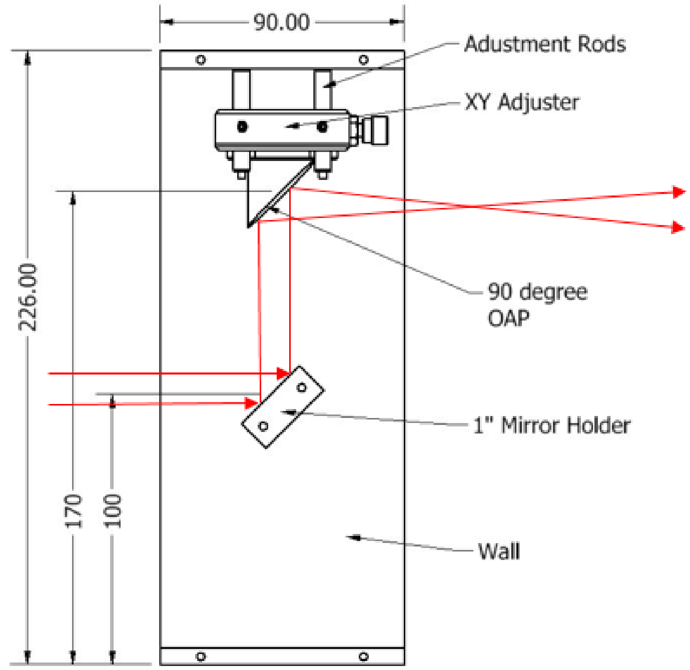


Fig. 3. A drawing of the periscope. Units are mm and the red lines indicate the path of light.

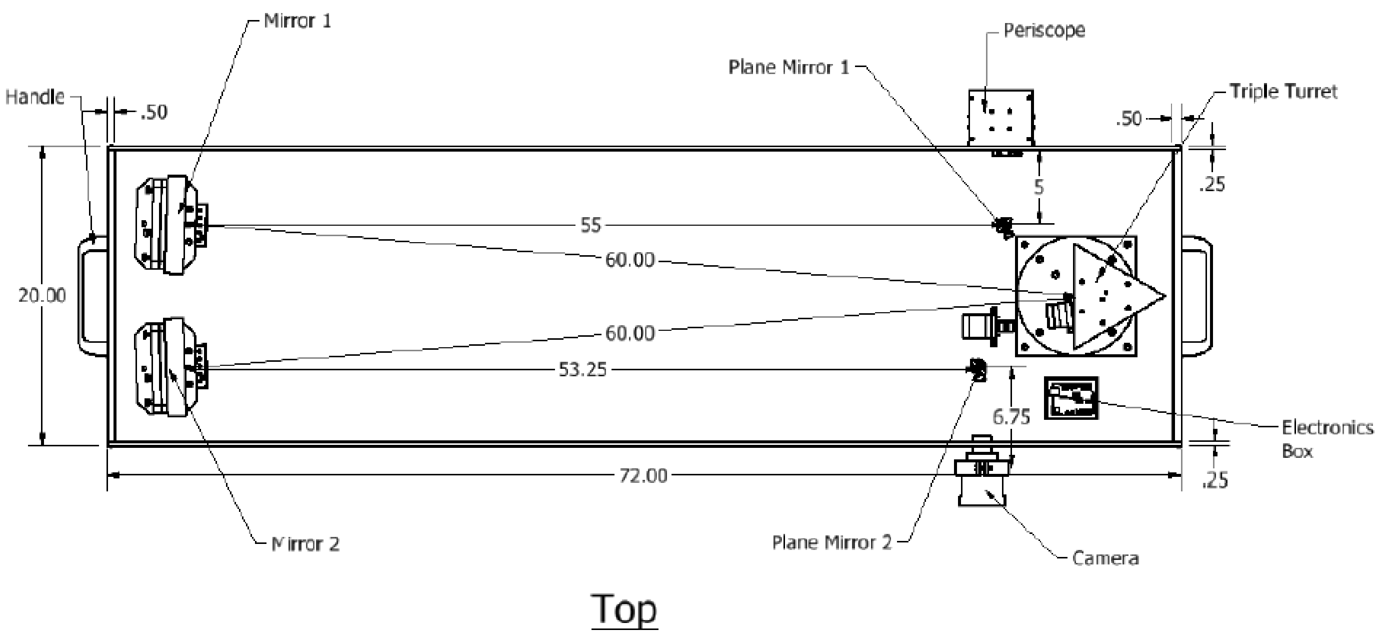


Fig. 8. A top view of the entire spectrometer. All units are inches.

Focal Length (cm)	50	50	50
λ1 (nm)	852	1550	852
λ2 (nm)	852.08	1550.04	852.05
Grating (lines/mm)	1200	1200	1800
Full Width 1/10th Max (um)	34.8	287	38.6

Figure 4

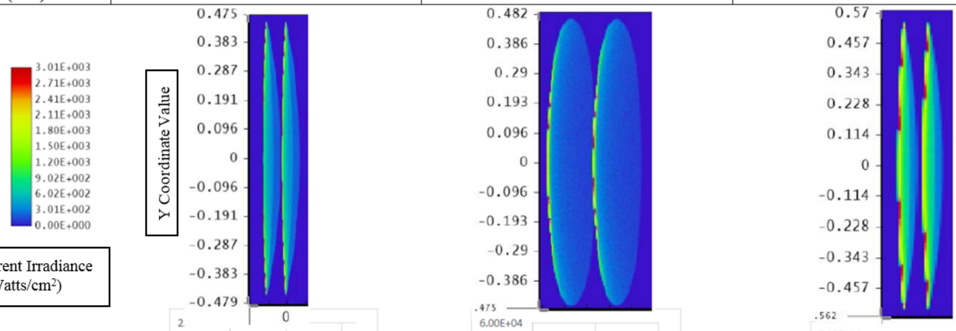
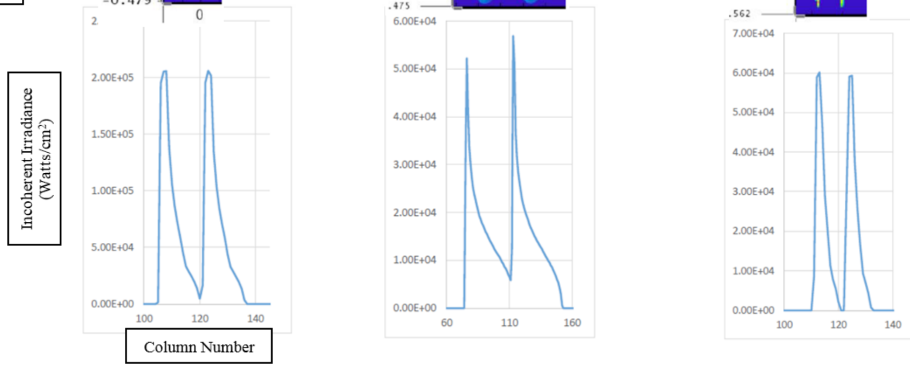


Figure 5



Focal Length (cm)	91	114	122	152
λ1, λ2 (nm)	852, 852.01	852, 852.01	852, 852.01	852, 852.01
Mirror Type	Parabolic	Spherical	Parabolic	Spherical
Full Width 1/10th Max	37	42	46.8	52.5
Distance Between Peaks	31	35	39.7	46

Figure 6

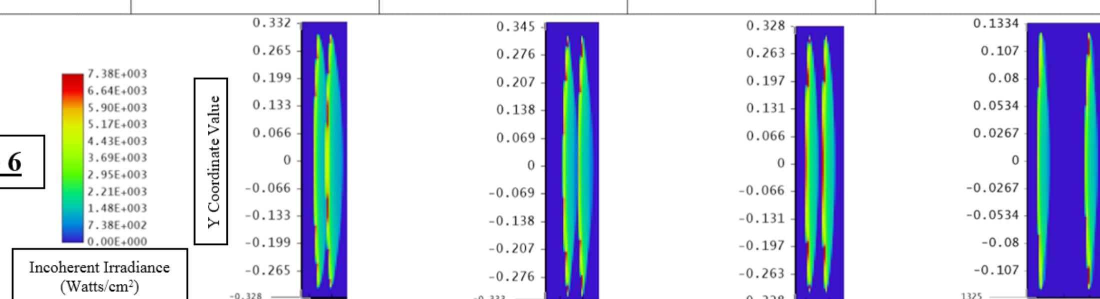


Figure 7