Enhanced Smartphone Spectroscopy via High-throughput Computational Slit

Emily Kuang University of Waterloo, ON, Canada
Farnoud Kazemzadeh University of Waterloo, ON, Canada
Alexander Wong University of Waterloo, ON, Canada

Abstract

High-performance spectroscopy is often limited by its portability, size, and cost, therefore limiting its reach into various applications that may benefit from it. In this paper, we present a low-cost, low-complexity slitless smartphone-based spectrometer that can be useful for carrying out field studies. Omitting a slit in a spectrometer means loss of spectral resolution in conventional spectrographs; however, we overcome this limitation via the use of a high-throughput computational slit to produce spectra with enhanced spectral resolution and enhanced signal-to-noise characteristics.

1 Introduction

Spectroscopy is a method of dissociating or dispersing light into its partial wavelength component, colors. This method is useful for various applications in numerous fields specifically for determining the molecular and atomic composition of material or inferring various state parameters of material such as pressure, magnetic field, temperature, etc. The field of spectroscopy is a rapidly growing field and spectrometers are quickly becoming ubiquitous in many fields of science and industry such as medicine, defense and security, pharmaceuticals, agriculture to name a few,

There have been many advances in spectrometer technology over the past decade that have decreased the size of these devices, miniaturizing them, and improved their performance, even making them available for consumer use [1, 2].

The performance of a spectrometer is determined by the spectral resolution ($\Delta\lambda$) and the light throughput efficiency, as characterized by the signal-to-noise ratio (SNR). There exists a proverbial battle between these two quantities as they are inversely proportional to each other and often plague the performance of spectrometers as one is maximized the other is minimized. This means that developing a high-resolution spectrometer for applications that are not photon-rich is a challenge.

Spectrometers are often characterized by the smallest wavelength component that can be discerned using them. Depending on the spectral resolution of this device, their applications can be limited. High-resolution spectrometers are often large to make up for any light losses as well as use highly sensitive detectors, the cost of which surpass all other components in the instrument. Therefore highly compact, portable, high-performance spectrometers are rarely available in the industry, even though applications for such devices are numerous. In this paper, we demonstrate a low-cost, low-complexity slitless smartphone-based spectrometer that is well-suited for carrying out various studies in the field.

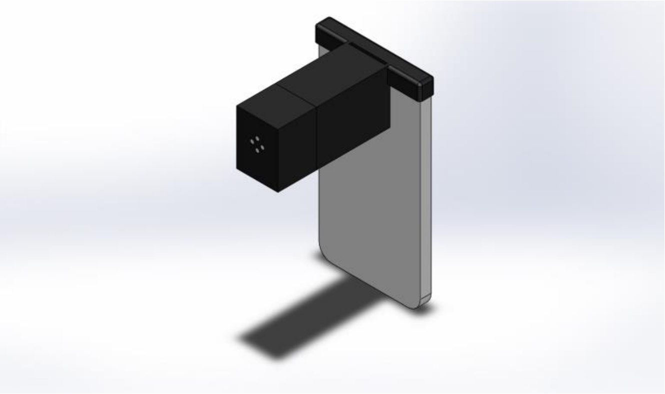

Fig. 1: Slitless smartphone spectrometer design.

2 Methodology

In general, a spectrometer consists of an entrance aperture which is usually a slit or a pinhole the width of which determines the spectral resolution of the instrument. The light that enters the instrument is then collimated using a lens and subsequently interacts with a diffraction grating which disperses the light. The dispersed light is then focused onto a detector using a lens and recorded by the detector as the spectrum of the incoming light.

Figure 1 shows a model of the slitless smartphone-based spectrometer. The spectrometer consists of two modular compartments that can be clipped onto a smartphone. The first compartment contains the diffraction grating (ruled transmission grating) and a fiber optic input (entrance aperture) for performing passive spectroscopy, and the second compartment contains a fiber optics probe accompanied with a series of light emitting diodes (LEDs) to enable active reflectance spectroscopy. The modular design allows for easy assembly of the optic fiber and LEDs and transfers between different LEDs. To determine the optimal distance between the entrance aperture, the grating, and the smartphone camera, an experiment was conducted with a series of lasers to ensure that the set of spectra from the first order of diffraction could be observed by the smartphone camera.

The entrance aperture to the spectrometer is a fiber optic cable with a core size of 105 µm, the grating used a ruled linear grating with a line density of 500 lines/mm, and the focusing optics is an f/1.4 lens of a smartphone. Given these specifications the theoretical spectral resolution of the device can be calculated to be > 25 nm with modest light throughput, using a 105 µm entrance aperture, which may not be sufficient for many field study applications. To overcome this limitation, the concept of high-throughput computational slit (HTCS) [3] is utilized to address this shortcoming in the presented smartphone spectrometer. Using HTCS, both the spectral resolution and efficiency of the spectrometer are significantly improved, thus enabling the proposed smartphone spectrometer to be a valuable field-deployable tool that can be used for various applications and field studies.

3 Results and Discussion

The first experiment performed using the smartphone spectrometer was to observe a Mercury-Argon spectral calibration light source. A spectral calibration light source is a light emitting device with precisely known and deterministic spectral features often used to calibrate a spectrometer. Figure 2 shows the image of the spectrum captured using the device accompanied by the plot of the measured spectrum, as well as the image and plot of the improved spectrum enhanced using HTCS. Six main features were expected to be observed in this spectrum, those are the emission lines at 404.66 nm, 407.76 nm, 435.84 nm, 546.08 nm, 576.96 nm, and 579.07 nm. These emission lines are referenced from Avantes. The first peak observed in the spectrum is the line at 404.66 nm and 407.76 nm mixed together which would suggest that the spectral resolution of the spectrometer is lower than ~ 3 nm. The second peak is at 435.84 nm, the third peak is at 546.09 nm, whereas the fourth peak is a combination of 576.96 nm and 579.07 nm. The emission lines > 680 nm were not observed since the smartphone camera employs a near infrared blocking filter.

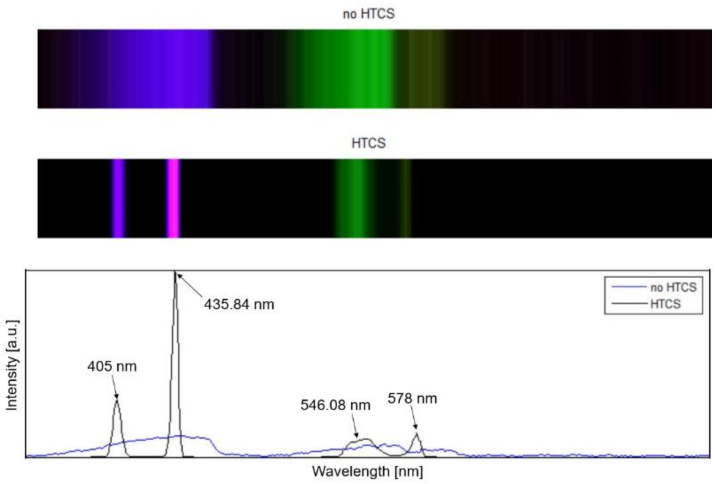

Fig. 2: Spectrum of mercury argon calibration source using the smartphone spectrometer (top), and enhanced using HTCS (middle) as well as the plot of the spectrum (bottom).

Using the calibration light source, the spectral resolution of the device can be determined. A Gaussian profile, which closely approximates a spectral emission line, was fitted to the spectral feature at 435.84 nm and the full-width-half-maximum of the profile was determined to be Δλ= 10 nm which is spectral resolution of the spectrometer.

The spectrum of a Mercury fluorescent lamp was captured using the smartphone spectrometer. This spectrum is captured in the form of an image and the raw capture spectrum and the improved spectrum enhanced using HTCS are both demonstrated in Figure 3. The extracted spectrum is shown in Figure 4a along with the HTCS-improved spectrum. The high-resolution ground-truth spectrum is shown in Figure 4b. It is observed that the measured spectrum is simply just a continuum of emission which corresponds to the white light that is emitted by such light bulbs. However, from the ground-truth spectrum it is apparent that there are distinct emission lines in these bulbs that combine to appear as white light. These distinct spectral features are clearly observed using the results from the smartphone spectrometer enhanced with HTCS. Thus the spectral resolution of the instrument using HTCS is improved such that the smartphone spectrometer can be utilized for applications and field studies that require such high resolution.

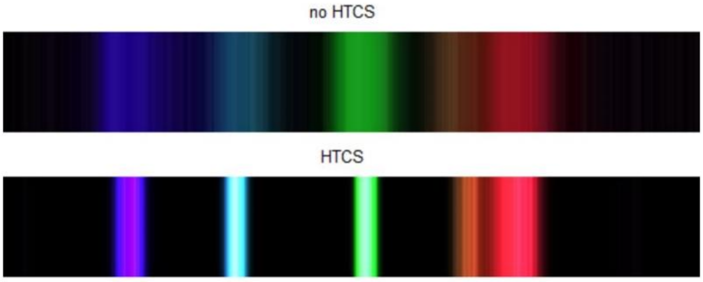

Fig. 3: Spectrum of mercury fluorescent lamp measured using the smartphone spectrometer (top), and enhanced using HTCS (bottom).

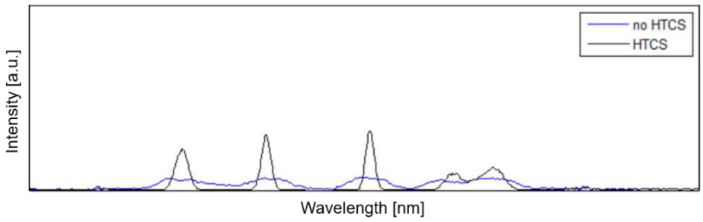

Fig. 4a: Spectral plot of the Mercury fluorescent lamp measured by the smartphone spectrometer, with and without HTCS.

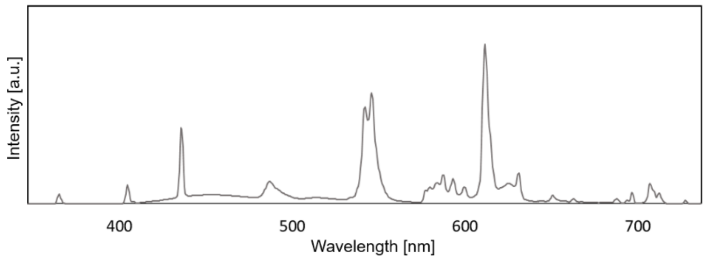

Fig. 4b: High-resolution spectrum of the mercury fluorescent lamp.

4 Summary

We have presented a low-cost, low-complexity slitless smartphone-based spectrometer with maximum light throughput while maintaining high spectral resolution. This slitless device, when accompanied by a high-throughput computational slit, has resulted in a high-resolution extremely efficient spectrometer that is light-weight, field-deployable, easy to use and very low level of complexity.

The spectral resolution of 10 nm has been demonstrated by measuring the spectrum of a Mercury-Argon calibration light source. Furthermore, the spectrum of a Mercury fluorescent light source has been measured and demonstrated to closely resemble the spectrum measured using a conventional high-resolution commercial spectrometer.

Smartphones have become increasingly popular over the past few years and are now widely used for both personal and professional reasons. Since the proposed device is an add-on to a smartphone, it is very convenient to use as it allows individuals to carry the module on their person which means that spectroscopy can be moved out of a laboratory setting.

Acknowledgement

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