RP Current Trends In Applied Sciences
Vol. 3, No. 1 (January – March 2024) pp. 1–6
e-ISSN: 2583-7486

RESEARCH PLATEAU
PUBLISHERS

Cite this article: S. Dutta, D. Paul, Design and development of smartphone spectrometer in visible domain, *RP Cur. Tr. Appl. Sci.* **3** (2024) 1–6.

Original Research Article

Design and development of smartphone spectrometer in visible domain

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ARTICLE HISTORY
Received: 27 Nov. 2023
Revised: 17 Jan. 2024
Accepted: 20 Jan 2024
Published online: 22 Jan. 2024

KEYWORDS
Smartphone; Spectrometer; Camera; Color filters; Absorption bands.

ABSTRACT
Optical spectroscopy is the scientific discipline addressing the interaction of matter with light through processes like emission and absorption. Various techniques, including emission spectroscopy, absorption spectroscopy, and fluorescence spectroscopy, contribute to this field. UV-VIS spectroscopy, a specific subset, operates on the principle that ultraviolet and visible light can excite π-bond and non-bonding electrons, causing absorption within the electromagnetic spectrum. UV-VIS spectroscopy boasts diverse applications across various fields. The tool commonly employed for optical spectroscopy investigations is an optical spectrophotometer. In the current research, a spectrophotometer was innovatively developed, utilizing a smartphone's camera as the detection unit. This system integrates basic laboratory optical components—pinholes, lenses, prisms, gratings—with the smartphone's camera module, enabling visible spectroscopy within the 400-700 nm wavelength range. The design prioritizes simplicity and accessibility in optical components, taking into account the need for device miniaturization. As a proof of concept, the smartphone spectrophotometer was demonstrated to measure absorption bands of commonly used color filters. Broadband light passing through these filters, positioned between the collimator and the cylindrical lens, allows transmitted light signals to be captured directly by the smartphone camera. This showcases the potential of using a smartphone as a spectrophotometer for practical applications. The resulting smartphone spectrophotometer is not only cost-effective but also robust and easily portable for field applications.

1. Introduction

The dispersion of white light into its individual components was first demonstrated by Newton in 1666, marking the inception of visible spectroscopy. Newton showcased how white light, upon passing through a glass prism, could be separated to create a spectrum of colors [1]. Optical spectroscopy, a scientific discipline dealing with the emission and absorption of light by matter, encompasses various types, including emission spectroscopy, absorption spectroscopy, and fluorescence spectroscopy. A widely employed spectroscopic method is ultraviolet-visible spectroscopy (UV-VIS spectroscopy), also known as ultraviolet-visible spectrophotometry. The underlying principle of UV-VIS spectroscopy lies in the excitation of π-bond electrons and non-bonding electrons by ultraviolet and visible light energy, enabling these electrons to absorb energy within these regions of the electromagnetic spectrum. UV-VIS spectroscopy finds diverse applications in different fields [2]. The essential instrument for studying optical spectroscopy is the optical spectrophotometer, comprising a light source emitting electromagnetic radiation across a broad wavelength range, a monochromator as the dispersive element, a sample holder for securing the sample, a detector to capture the output light signal, a signal processing system, and a readout unit [3]. The spectrophotometer quantifies the transmittance of a solution, defined as the ratio of the intensity of light transmitted by the sample to that of the reference blank:

$$T = \frac{I}{I_0} \tag{1}$$

Here I is the intensity of light transmitted by the sample and I_0 is the intensity of light transmitted by the reference blank % transmittance is measured as:

$$\%T = \frac{I}{I_0} \times 100 \tag{2}$$

The absorbance (or optical density) is measured from the transmittance by the following relation:

$$A = -\log T \tag{3}$$

which shows that the absorbance is related to transmittance logarithmically.

In this current work, a spectrophotometer has been innovatively developed using the smartphone's camera as the detection unit. Basic laboratory optical components have been seamlessly integrated with the smartphone's camera module to create a spectrophotometer capable of performing visible spectroscopy within the wavelength range of 400-700 nm. The subsequent sections delve into the optical components utilized and the corresponding optics design.

2. Materials and methods

The spectrophotometer for smartphones was crafted utilizing readily accessible laboratory optical components like pinhole, lens, prism, grating, and more. The selection of these components prioritized the miniaturization aspect in device manufacturing. Figure 1 provides an overview of the optical elements employed in designing the spectrophotometer, specifically in direct coupling mode.

Figure 1: Optical components used in the spectrometer.

2.1 *Light source*

To conduct a spectroscopic study, it is crucial to select a consistent light source capable of emitting spectral radiation across a broad wavelength range, spanning from ultraviolet to the infrared region. A tungsten halogen lamp proves to be an optimal choice as it can emit electromagnetic radiation from the visible to the near-infrared spectrum. In this study, an LS-1 tungsten halogen lamp from Ocean Optics, powered by a 12 V VDC regulated power supply, serves as the light source. The lamp's spectral radiation range is 360-2000 nm. Figure 2(a) displays a photograph of the halogen light source, while Figure 2(b) showcases the optical fiber patch cord (P200-I-VIS-NIR, Ocean Optics) employed to link the light from the broadband source to the smartphone spectrometer. The fiber patch cord has a core diameter of 200 µm and is one meter long. Figure 3 illustrates the spectrum profile of the broadband light source, measured using an optical fiber spectrometer (BLK-C-SR, StellarNet BLACK-Comet). Due to the spectrometer's limitations, it could only measure the spectrum of the broadband source in the range of 200-1100 nm.

2.2 Aperture optics

In order to regulate the brightness of the light emanating from the broadband source and prevent undesired noise caused by stray light interference, it is essential to restrict the influx of a large number of photons into the system. To achieve this, a 50 µm diameter pinhole (EO) has been incorporated into the system's design. The primary objective of the pinhole is to achieve a point source of light rather than an extended source. In cases where the light signal passing through the pinhole is too diminished, larger pinhole sizes such as 75 µm or 100 µm can also be employed.

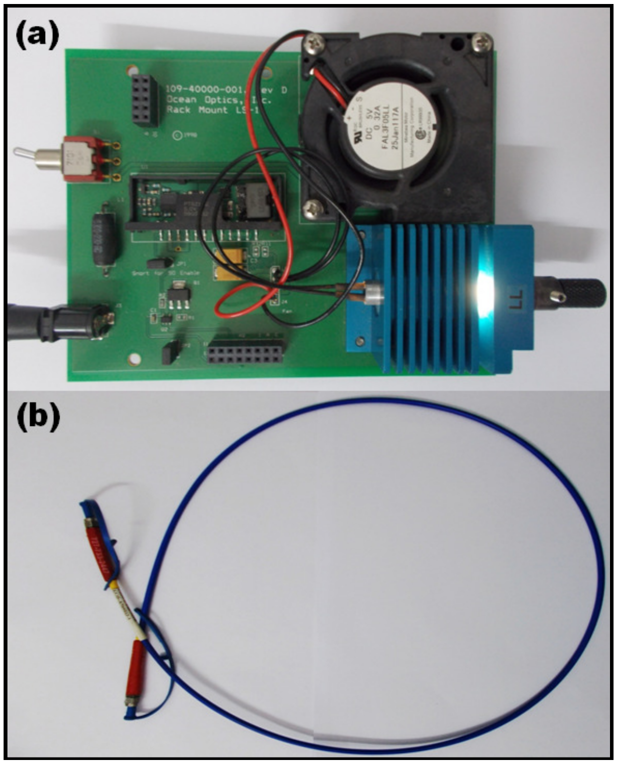

Figure 2: Photo image of the (a) Light source (LS-1, Ocean Optics) and (b) Optical fiber used for coupling the light from the source.

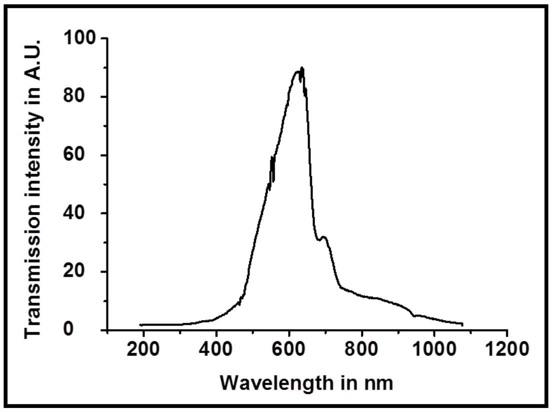

Figure 3: Spectrum profile of the broadband light source (LS-1, Ocean Optics) from 200-1100 nm measured using optical fiber spectrometer.

2.3 Focusing optics

The smartphone's camera is equipped with an actuator that can move the lens along the optical axis. An embedded algorithm is responsible for determining the optimal position of the lens, ensuring the production of high-contrast images with sharp edges [4]. In the designed smartphone spectrophotometer, a plano-convex lens is employed for collimating the light signal from a point source, while a cylindrical lens is used to generate a focused line beam, thereby achieving the desired spectrum.

Plano-convex lens: To address the divergence of light rays emerging from the pinhole and align the diverging beam in a parallel manner, a plano-convex lens is utilized in this setup. The lens has a diameter of 10 mm and a focal length of 75 mm. The positioning of the pinhole relative to the plano-convex lens is meticulously adjusted to maintain the pinhole at the focal plane of the lens, ensuring proper collimation of the light beam from a point source.

Cylindrical lens: Apart from the plano-convex lens, a cylindrical lens has been employed for the purpose of focusing. The primary role of the cylindrical lens is to converge the collimated light beam into a line beam. This convergence results in the concentration of photons into a single line, consequently enhancing the signal-to-noise (S/N) ratio of the recorded spectrum [5]. The diffraction grating stands out as a crucial optical component essential for the construction of a spectrophotometer [6]. Diffraction gratings come in two main types: transmission grating and reflection grating. The distinction between transmission and reflection grating hinges on the incident and diffracted rays of light interacting with it. In a reflection grating, both incident and diffracted rays fall on the same side of the grating, whereas, in a transmission grating, the incident and diffracted rays are situated on opposite sides of the grating. A grating disperses a beam of light at specific angles, and angular dispersion is contingent on the groove spacing and incident angle. A reduction in groove spacing or an increase in the angle of incidence leads to heightened angular dispersion.

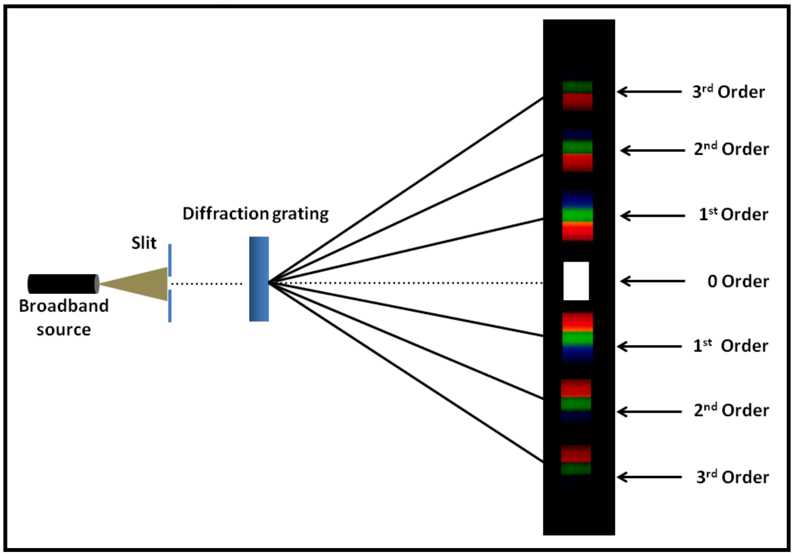

Figure 4: Dispersed image spectrum of the broadband source depicting different orders of diffraction.

Equation (4) relating the angle of incidence, angle of diffraction and groove spacing is given as:

$$m\lambda = d\,(\sin\alpha + \sin\beta) \tag{4}$$

where α represents the value of angle of incidence, β denotes the angle of diffraction, *d* is the groove spacing, λ represents the wavelength of incident light, m is the spectral order of diffraction which is an integer value.

For the transmission grating employed in this study, the first-order dispersion occurs at approximately 470 concerning the zero order. The first-order (m = 1 or m = -1) dispersed spectrum exhibits greater intensity than higher-order spectra, a characteristic property of diffraction. In the optical system design, the alignment of the smartphone is configured so that the first-order spectrum aligns with the phone's camera and is observable on its display panel. Figure 4 illustrates the dispersed spectrum of the broadband light source diffracted at different angles for various orders of diffraction.

2.4 Detector

The optical detector utilized for the spectrophotometer is the rear camera module of an Apple iPhone 4. All images were captured in autofocus (AF) locked mode.

3. Design of the smartphone spectrometer

The schematic diagram of the sensor designed for direct coupling sensing is depicted in Figure 5(a). In this configuration, a broadband optical source emits a light signal that passes through a 50 µm pinhole (Edmund Optics) and then through a collimating lens (FL 75 mm, Edmund Optics). The resulting collimated light beam travels through the test sample (poured in a quartz cuvette with a 5 mm path length for liquid sample) or passes colored filters. Subsequently, the light passes through a pair of cylindrical lenses (FL 50 mm, Edmund Optics) and a planar transmission grating (1200 lines/mm, Edmund Optics) to reach the smartphone's camera. The transmission grating is integrated with the smartphone's camera. The transmitted modulated light beam contains information about the wavelength absorption bands of the specific sample, detectable by the designed sensing setup. In this setup, the rear camera (5 Mega pixel) of an iPhone 4 (Apple Inc.) is employed for image capture, and the images can be viewed on the phone's display panel. These images can be transferred to a desktop for post-processing activities through Bluetooth or the existing mobile network. Figure 5(b) provides a handheld photograph of the designed sensing system, with the cuvette positioned in the optical path of the setup.

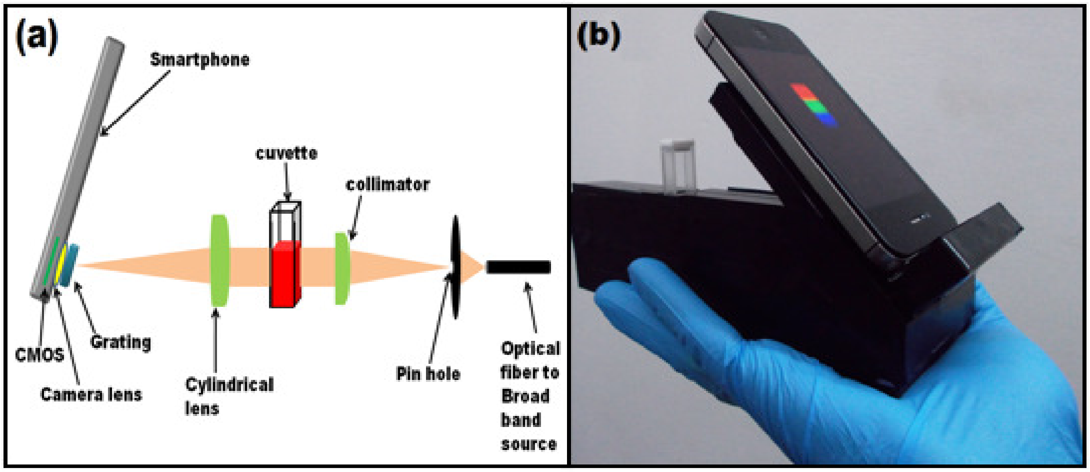

Figure 5: (a) Schematic of the smartphone spectrophotometer in direct coupling mode and (b) Photo image of the hand held sensor.

3.1 Pixel to wavelength calibrations

Before commencing the sensing investigation, the visible spectrum information recorded through the smartphone's camera is calibrated into a wavelength scale based on pixels. Initially, the dispersed spectrum of the broadband source is captured by the smartphone's camera. Subsequently, the broadband optical source is replaced sequentially by three diode laser sources with known wavelengths: 405 nm (blue laser), 533 nm (green laser), and 655 nm (red laser). ImageJ software [7] is employed to identify the pixel positions of these standard laser sources. The pixel positions of these lasers are plotted against their corresponding wavelength values. Through linear fitting of pixel positions with wavelength values, an excellent linear fit is achieved with an R^2 value of 0.9999, as depicted in Figure 6 (a). Consequently, the pixel-to-wavelength calibration exhibits a strictly linear variation trend between pixel positions and wavelength values along the dispersive direction. The empirical relation between pixels and wavelength is described by the linear-fitted calibration equation:

$$y = 0.337*x + 170.25 \tag{5}$$

where y is wavelength and x is the pixel position. Thus, equation (5) can also be written as:

$$\text{wavelength} = 0.337*\text{pixel position} + 170.25\ \text{nm} \tag{6}$$

Equation (6) correlates pixel position with wavelength. By inputting specific pixel values into the pixel position, the corresponding wavelength can be easily predicted. Assuming a linear relationship between pixel positions and corresponding wavelengths, the linear-fitted calibration equation (5) is utilized to convert the pixel scale into the wavelength scale. Figure 6(b) illustrates the characteristic intensity distribution of all three laser sources, along with the spectrum of the broadband source measured by the designed sensing setup. The figure presents the plot of intensity distribution along the Y-axis with the corresponding wavelength along the bottom X-axis and pixels involved along the top X-axis. The pixel-to-wavelength calibration reveals that for each pixel shift, there is a corresponding wavelength increment of 0.337 nm.

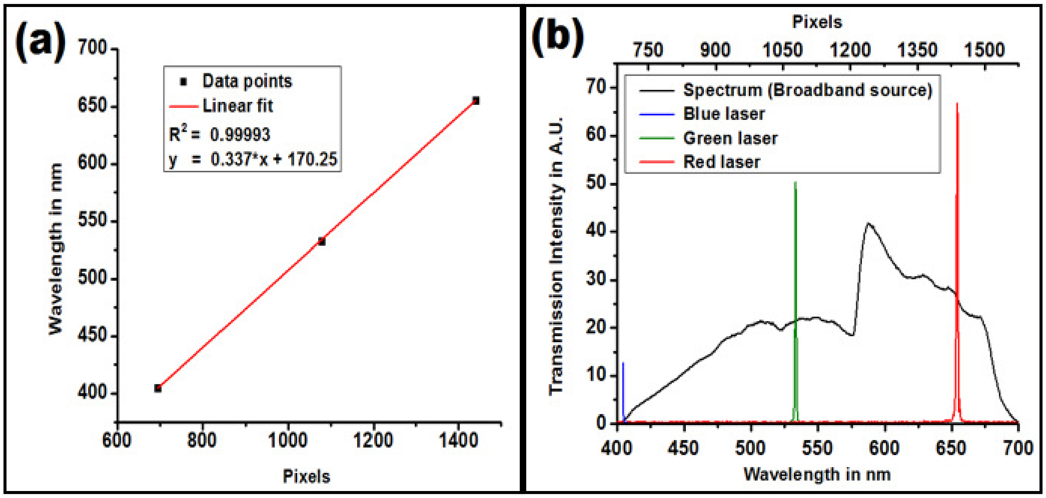

Figure 6: (a) Linear fit for pixel versus wavelength variation for three standard laser sources and (b) Pixel to wavelength calibrated graph for bare spectrum and three different laser sources.

Table 1 displays the wavelengths of the standard laser sources along with their corresponding pixel positions as measured by the developed system.

Table 1: Pixel positions of the standard laser sources.

Lasers	Wavelength	Pixel position
Blue Laser	405 nm	695
Green laser	533 nm	1078
Red laser	655 nm	1439

Figure 7 illustrates the spectrum profiles of both the broadband light source and the three laser pointers employed for calibration as measured by the standard spectrometer.

The smartphone spectrophotometer designed here utilizes affordable optical components.

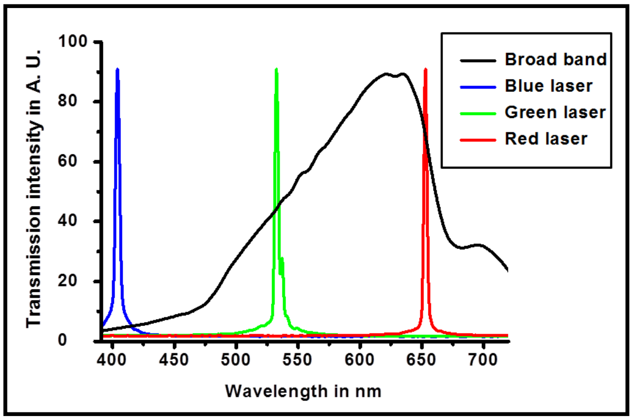

Figure 7: Spectral profile of the broadband light source along with that of red, green and blue laser pointers, measured using standard fiber optic spectrometer (BLK-C-SR, StellarNet BLACK-Comet).

Figure 8: Photographic images of the colored filters whose absorption bands have been measured.

3.2 Measuring absorption bands of color filters in direct coupling mode

In this study, a variety of color filters with transmission bands centered at 460 nm, 500 nm, 540 nm, 570 nm, and 635 nm were utilized (refer to Figure 8). The configuration of the direct coupling mode setup has been previously elucidated in section 3.

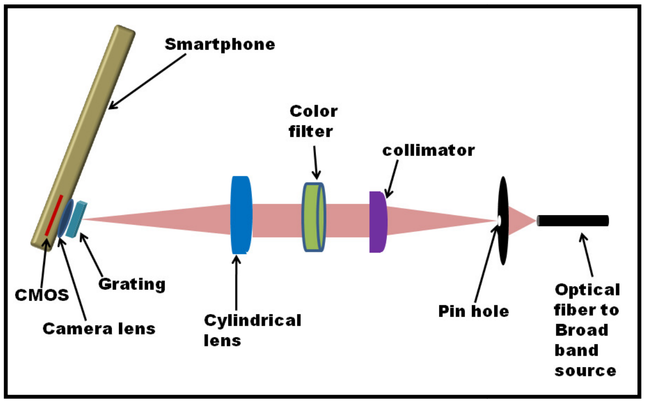

Figure 9: Schematic of the designed sensor in direct coupling mode.

Figure 9 illustrates the schematic of the sensor designed to measure absorption bands of the filters. The process involves directing a collimated light beam (broadband) through a plano-convex lens onto a color filter. The modulated light beam is then focused into a line beam using a cylindrical lens. Subsequently, the focused line beam encounters a transmission grating, dispersing it into a visible spectrum, which is recorded by a smartphone's camera. Various absorption bands become apparent in the dispersed image spectrum, contingent on the specific filter positioned in the optical path.

Figure 10(a) displays the characteristic transmission spectrum of the broadband light source, along with the transmission spectra of modulated light beams after passing through distinct color filters. The depiction makes it evident that diverse color filters showcase distinct transmission bands when exposed to white light.

The CMOS image sensor in the smartphone camera exhibits sensitivity in the wavelength range of 410 to 680 nm, with sensitivity diminishing beyond this range, as indicated by the characteristic transmission spectra of the broadband light source in Figure 10(a). Consequently, the designed sensor proves adept at detecting spectral changes (absorbance or transmittance) within the wavelength regime of 410 to 680 nm with considerable sensitivity.

To validate the obtained results, the transmission bands of the same filters were measured using a laboratory-grade spectrophotometer (UV-3101PC, SHIMADZU) in spectrum mode, as depicted in Figure 10(b). A comparison of the data from the standard spectrophotometer with that from the designed sensor revealed nearly identical variations in transmission spectra. This affirms the capability of the designed sensor for conducting spectroscopic-based sensing investigations in the visible domain.

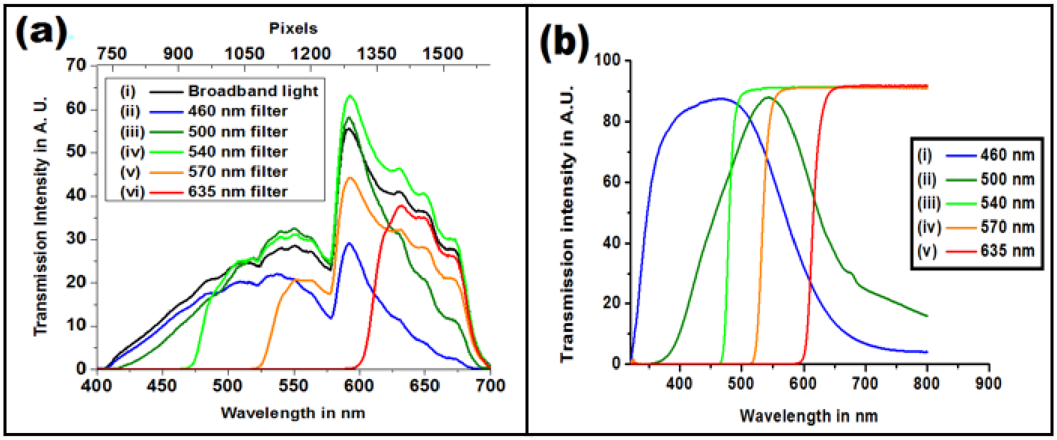

Figure 10: Characteristic transmission spectrum of colored filters measured using (a) smartphone sensor and (b) standard spectrophotometer.

4. Conclusions

The potential of a smartphone-based spectrophotometer has been explored using readily available, affordable laboratory optical components. The calibration process, transitioning from pixels to wavelength units for this spectrophotometer, has been achieved through the utilization of low-cost laser pointers, widely accessible in the market. The calibration results indicate a dispersion value of 0.337 nm/pixel for the current smartphone-spectrophotometer. To enhance versatility, various colored filters were integrated into the optical path, and their transmission spectra were captured. This smartphone spectrometer is characterized by its robustness, reliance on inexpensive optical components, portability for field use, and capability to share in-field sensing data globally through existing cellular networks. The innovation holds promise for revolutionizing field portable sensing in economically disadvantaged regions across globe.

Acknowledgements

The authors are thankful to Prof. (Dr.) P. Nath for providing support and facilities for the research work.

References

[1] N. C., Thomas, The early history of spectroscopy, *J. Chem. Edu.* **68** (1991) 631.

[2] H.H. Perkampus, H.C.Grinter, T. Threlfall, *UV-VIS Spectroscopy and its Applications*, Springer, Berlin (1992).

[3] B. Clark, T. Frost, M. Russell, *UV Spectroscopy: Techniques, Instrumentation and Data Handling*, Chapman & Hall, London (1993).

[4] https://www.westfloridacomponents.com/blog/how-does-a-smartphone-camera-autofocus/. Archived 06 December 2023.

[5] M. A.Hossain, J. Canning, J, S. Ast, K. Cook, P.J.Rutledge, A. Jamalipour, Combined "dual" absorption and fluorescence smartphone spectrometers, *Opt. Lett.* **40** (2015) 1737-1740.

[6] E. G. Loewen, E. Popov, Diffraction Gratings and Applications, CRC Press, New York (1997).

[7] https://imagej.nih.gov/ij/. Archived 06 December 2023.