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Compact Spectrometer by Unitizing Thin Film Interference

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Compact Spectrometer by Unitizing Thin Film Interference

by

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ABSTRACT

Optical spectrometer is an instrument to analyze light's property by showing the intensity of the light in different frequencies. Therefore, it is a popular tool to study the interaction between matter and electromagnetic radiation, which is beneficial to so many research fields such as material science, chemistry, astronomy, and etc. Traditionally, the optical spectrometer uses either grating or prism to refract light to perform the measurement of the light intensity in different wavelengths. In this report, a different approach is discussed to build a compact optical spectrometer. By using a thin film, a phenomenon called thin film interference, whose patterns can be used to determine the intensities in various frequencies, occurs when an incoming light beam is focus on the thin film.

In this project, a CMOS camera manufactured by ZWO is used to detect and record the light intensity. There are two types of lens being used: cylindrical lens and convex lens. The cylindrical lens helps shape the incoming laser beam into line patterns; while the convex lens reflects the light to focus at one point on the thin film. Finally, the CMOS camera can store the images of the light passing through the thin film. By knowing the transmission matrix of the thin film, the images can help calculate the frequency domain profiles of the detected light signal.

CHAPTER 1.   INTRODUCTION

1.1 MOTIVATION

Unquestionably, optical spectrometer has become an important equipment to perform measurement on interaction between matter and electromagnetic radiation. It plays a key role in determine materials' physical or optical property. For instant, in semiconductor characterization, by investigating the conversion of the input optical signal in frequency domain, absorption coefficient, film thickness, and band gap can be found. Besides semiconductor characterization, optical spectrometer is also important to the research fields such as chemistry and astronomy. Traditionally, the optical spectrometer uses either grating or prism to refract light to perform the measurement of the light intensity in different wavelengths as illustrated in **Fig. 1**. Designing a compact spectrometer with low cost and better performance is very beneficial to both research and industry. And the new approach of using a thin film as a media to cause the pattern of thin film interference (See **Fig. 2**) has a huge potential to make a low cost compact spectrometer.

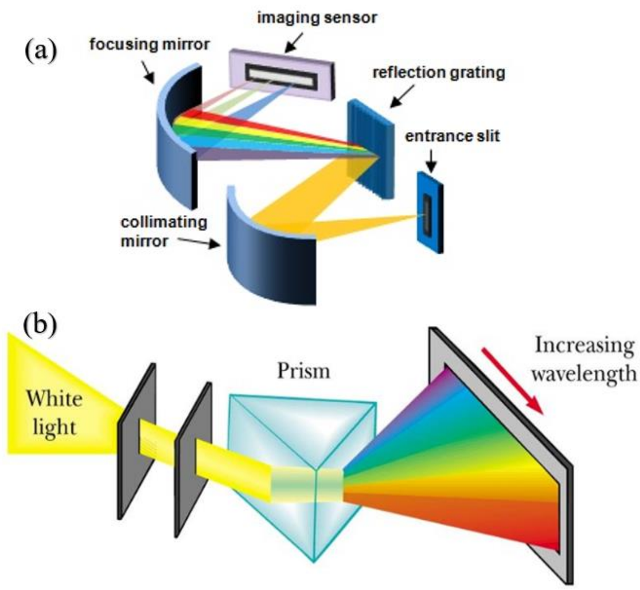

Fig. 1 Two types of transitional optical spectrometers using light refraction: (a) the structure of the optical spectrometer using grating [1]; (b) the structure of the optical spectrometer using prism [2].

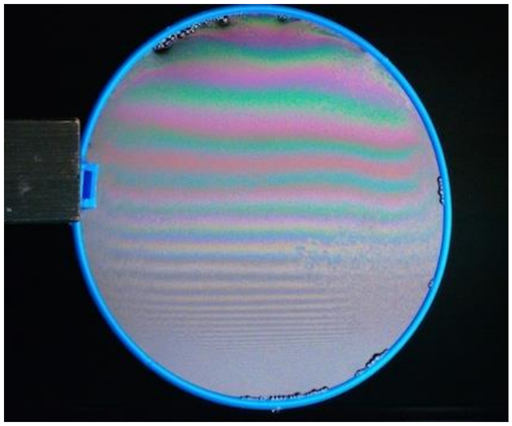

Fig. 2 A thin film experiment demonstrated by using the soap film [3].

1.2 OUTLINES

Chapter 2 describes the mathematical models for the thin film interference. First, the wave field propagation at an interface between two media with different refractive indexes is discussed. Then, the mathematical expression of the overall reflectance for the case that the wave field propagates along three different media is illustrated. In the second part of chapter 2, the calculated light transmission rate for the thin film purchased from Thorlabs in different frequencies is compared with the measured transmission rate downloaded from Thorlabs' website.

Chapter 3 focus on introducing the principle and design of the new compact spectrometer. The first part illustrates how the functionality of the compact spectrometer can be achieved by knowing the transmission matrix of the thin film. And the second part talks about the structure of the compact spectrometer. Finally, the result of a preliminary measurement by using a red light laser point is demonstrated.

Chapter 4 is the conclusion of this report. It presents a summary of the work for this project. The future plans and improvements are discussed.

CHAPTER 2. THIN FILM INTERFERENCE

2.1 THEORY OF THIN FILM INTERFERENCE

Thin film interference is a phenomenon that the reflected light by a thin film could be either enhanced or reduced on light intensity. And the intensity of the reflected light depends on the thickness of the thin film and the wavelength of light. It arises from the propagation of light at the interface. For the electromagnetic wave propagation at an interface (from refractive index n_1 to n_2, as seen in **Fig. 3**), the perpendicular component E_s and parallel component E_p of an electric field show different behaviors on reflection, which can be described by the following equations about the Fresnel coefficients r_s and r_p:

$$r_s = \frac{E_{s,r}}{E_{s,i}} = \frac{n_1 \cos\theta_1 - n_2 \cos\theta_2}{n_1 \cos\theta_1 + n_2 \cos\theta_2} \qquad (2.1)$$

$$r_p = \frac{E_{s,r}}{E_{s,i}} = \frac{n_2 \cos\theta_1 - n_1 \cos\theta_2}{n_2 \cos\theta_1 + n_1 \cos\theta_2} \qquad (2.2)$$

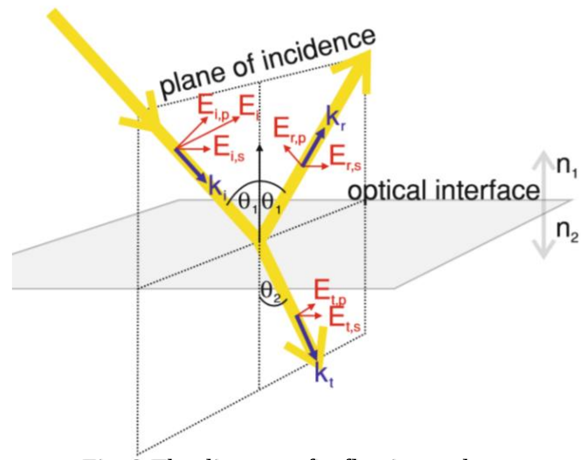

Fig. 3 The diagram of reflection and refraction at an optical interface [4]

The Fresnel coefficients r_s and r_p are the reflection coefficients for the single interface corresponding to the perpendicular component and the parallel component of an incident field wave. As illustrated in **Fig. 4**, the incident field can cause infinite reflected fields within the thin film and outside the thin film. The summation of the reflected components outside the thin film would be the overall reflection of the system. For finding the summation, the optical path difference δ between two neighboring reflected rays can be expressed as the following equation:

$$\delta = 2n_1 l = 2n_1 h \cos\theta_1 \qquad (2.3)$$

In the formula above, l represents the single physical optical path in the thin film, and h

stands for the thickness of the thin film. Between two neighboring reflected rays in **Fig. 4**, it is clear that there are two optical paths $n_1 l$ contributing the optical path difference δ.

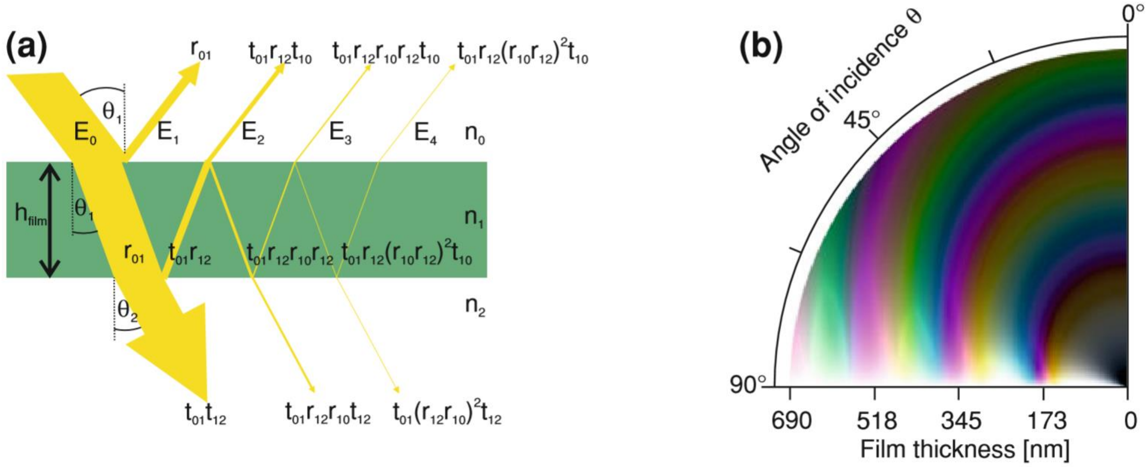

Fig. 4 Thin film interference [4]: (a) reflection and refraction model of the thin film interference; (b) illustration of the color reflection of a thin film plotted by computer-simulation

Therefore, the phase shift $\emptyset$ can be described below as:

$$\emptyset = (m+1)\frac{2\pi}{\lambda}\delta \tag{2.4}$$

In equation (2.4), m represents the number of total internal reflections, while λ is the wavelength of the field wave. And the summation of the reflected components R outside the thin film could be calculated as below [4]:

$$r = \frac{E_r}{E_0} = \frac{E_1}{E_0} + \frac{E_2}{E_0} + \frac{E_3}{E_0} + \cdots = r_{01} +$$

$$t_{01}\, r_{12} t_{10} \exp(-i\phi)\ \sum_{k=1}^{\infty}(-1)^k (r_k r_{10})^k \exp(-ik\phi) = \frac{r_{01}+r_{12}\exp(-i\phi)}{1+r_{10}r_{12}\exp(-i\phi)} \tag{2.5}$$

$$R = r^2 = \frac{r_{01}^2 + r_{12}^2 + 2r_{01}r_{12}\cos\emptyset}{1 + r_{01}^2 r_{12}^2 + 2r_{01}r_{12}\cos\emptyset} \tag{2.6}$$

By using the equation (1.6), the reflectance of perpendicular and parallel components, R_s and R_p, can be calculated. And the overall reflectance R_{eff} is the average of R_s and R_p:

$$R_{eff} = (R_s + R_p)/2 \tag{2.7}$$

2.2 THIN FILM INTERFERENCE TRANSMISSION PROFILE SIMULATION

At the end of the section 2.1, the mathematical expression of the reflectance in a three-media system is discussed. For the thin film interference, the middle media is the thin film while others are air. Therefore, by assuming the air/thin film interface has reflection coefficients r_s and r_p (can be calculated from equations (2.1) and (2.2)), the mathematical expressions for R_s and R_p can be simplified as the following equations:

$$R_s = \frac{2r_s^2 + 2r_s^2 \cos \emptyset}{1 + 2r_s^2 + 2r_s^2 \cos \emptyset} \tag{2.8}$$

$$R_p = \frac{2r_p^2 + 2r_p^2 \cos \emptyset}{1 + 2r_p^2 + 2r_p^2 \cos \emptyset} \tag{2.9}$$

By taking the average between R_s and R_p, the effective overall reflectance can be calculated. Furthermore, by assuming there is no absorption on the thin film, the transmission can be calculated by the following formula:

$$T = 1 - R_{eff} \tag{2.10}$$

For the transmission of the wave field propagation through the thin film, there are two variables. They are frequency λ and incident angle θ. The properties of the thin film can also affect the transmission. For the thin film (BP108) purchased from Thorlabs, it is made of nitrocellulose, which has a refraction index of 1.5 at wavelength of 550 nm [5]. And its thickness is around 2.51 micrometer. By using the equations (2.8) to (2.10), the plot of transmission vs wavelength at a fixed angle, or the plot of transmission vs angle at a fixed wavelength can be made, and as illustrated in **Fig. 5**. What's more, the comparison between the calculated transmission vs wavelength plot and the measured one downloaded from Thorlabs [5] can also be seen in **Fig. 6**.

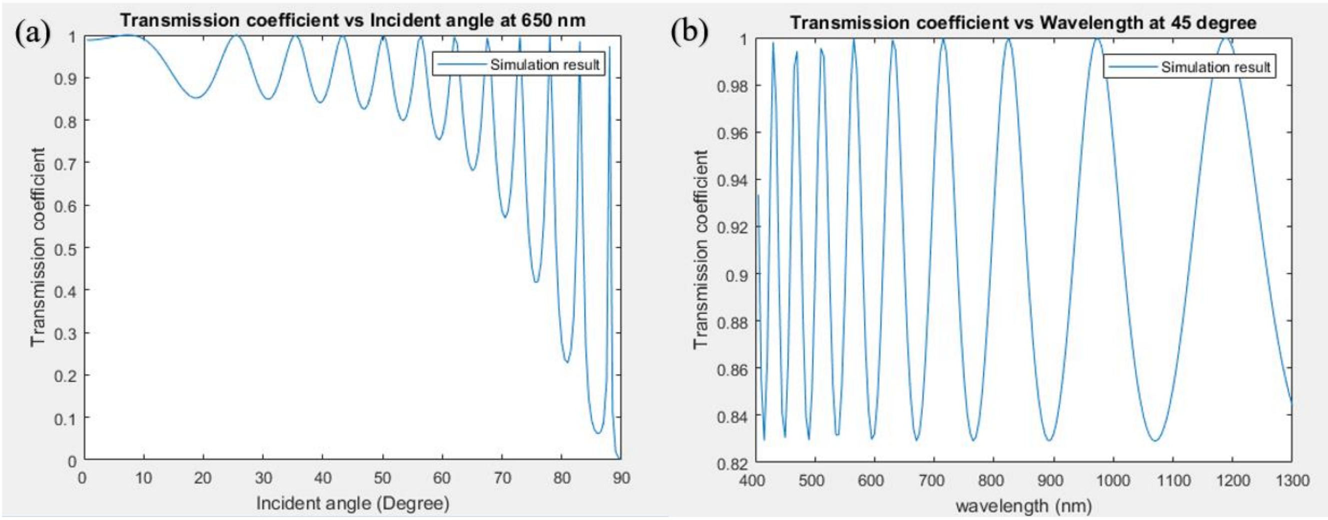

Fig. 5 Results of the thin film interference simulation in MATLAB: (a) plot of transmission coefficient vs incident angle at 650 nm; (b) plot of transmission coefficient vs wavelength at 45 degree of incident angle

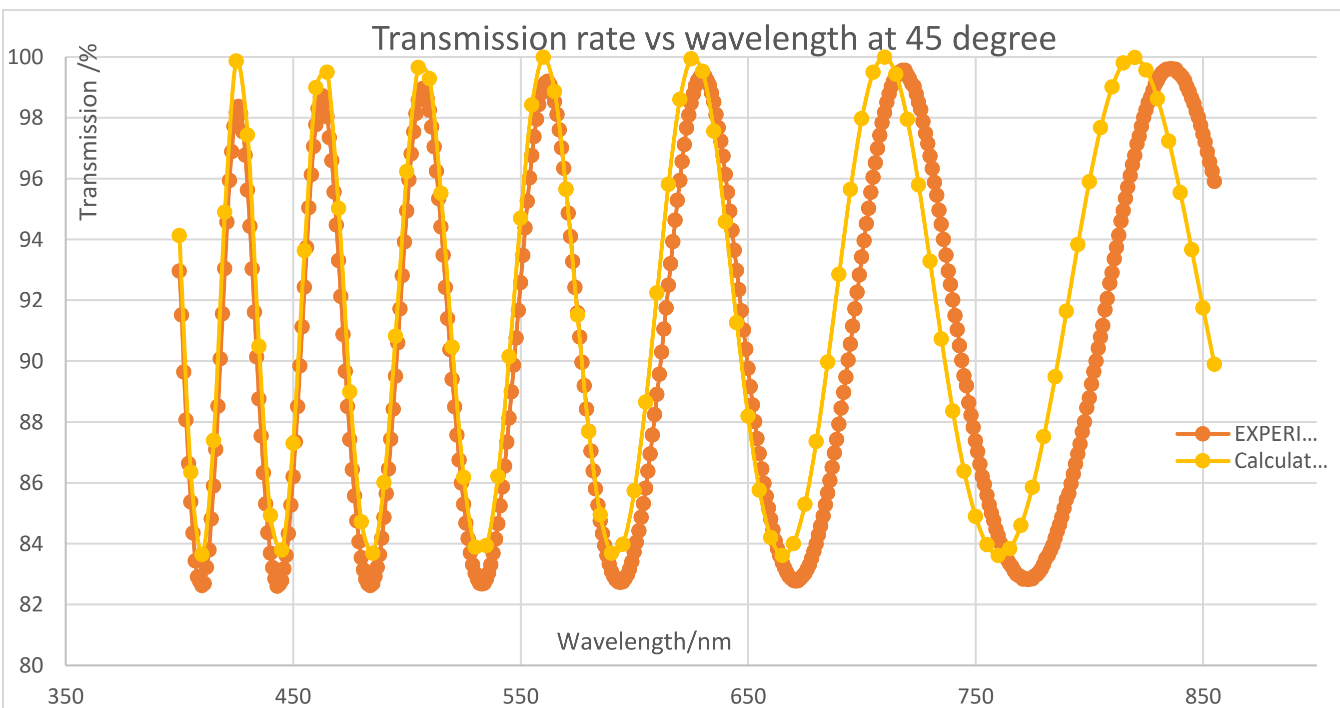

Fig. 6 Comparison of the simulated transmission vs wavelength plot in Excel and the measured one from Thorlabs [5] at 45 degree of incident angle. In the simulation, the refraction index keeps the same as 1.5 and there is an assumption of no absorption on the thin film.

CHAPTER 3. COMPACT SPECTROMETER

3.1 TRANSMISSION MATRIX OF THE THIN FILM

The transmission matrix of the thin film is a square matrix containing information of transmission coefficients under various incident angles and wavelengths of the optical signal (See **Fig. 7 (b)**). For the transmission matrix $\vec{T}$, its horizontal elements are the transmission coefficients with a fixed incident angle and various wavelengths ranging from λ_1 to λ_N. Similarly, the vertical elements are the transmission coefficients with a fixed wavelength and various incident angles ranging from θ_1 to θ_N. In **Fig. 7**, $\vec{I}$ represents the measured light intensity on CMOS camera; while $\vec{S}$ is the light intensity of the unknown input light spectrum. Therefore, by taking the inverse of the transmission matrix $\vec{T}$ to get $\overrightarrow{T^{-1}}$, the spectrum of the unknown optical signal can be calculated by the following equation:

$$\vec{S} = \overrightarrow{T^{-1}}\,\vec{I} \tag{3.1}$$

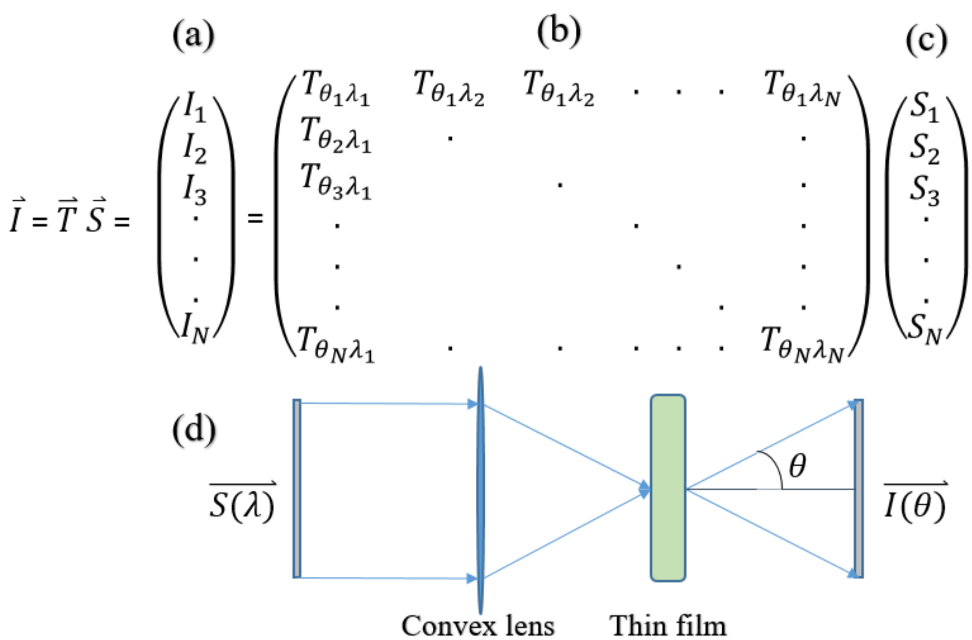

Fig. 7 Explanation of using transmission matrix of the thin film and detected light intensity on CMOS camera to find out the spectrum of the input optical signal: (a) matrix of measured intensity on CMOS camera $\vec{I}$; (b) transmission matrix of the thin film; (c) matrix of the unknown input light spectrum; (d) diagram of the light propagation in the spectrometer

By creating a matrix in MATLAB and inputting the transmission coefficients into the elements of the matrix based on the equations in chapters **2.1** and **2.2**, and the transmission matrix format in **Fig. 7**, the simulated transmission matrix for the thin film can be calculated. Getting the inverse of the transmission matrix can be easily done in MATLAB by using inv() function. As illustrated in Fig. 8, by assuming the input optical signal consists of 20% of 500 nm component, 50% of 600 nm component, and 30% of 700 nm component to get $\vec{I}$, $\vec{S}$ can be calculated and plotted.

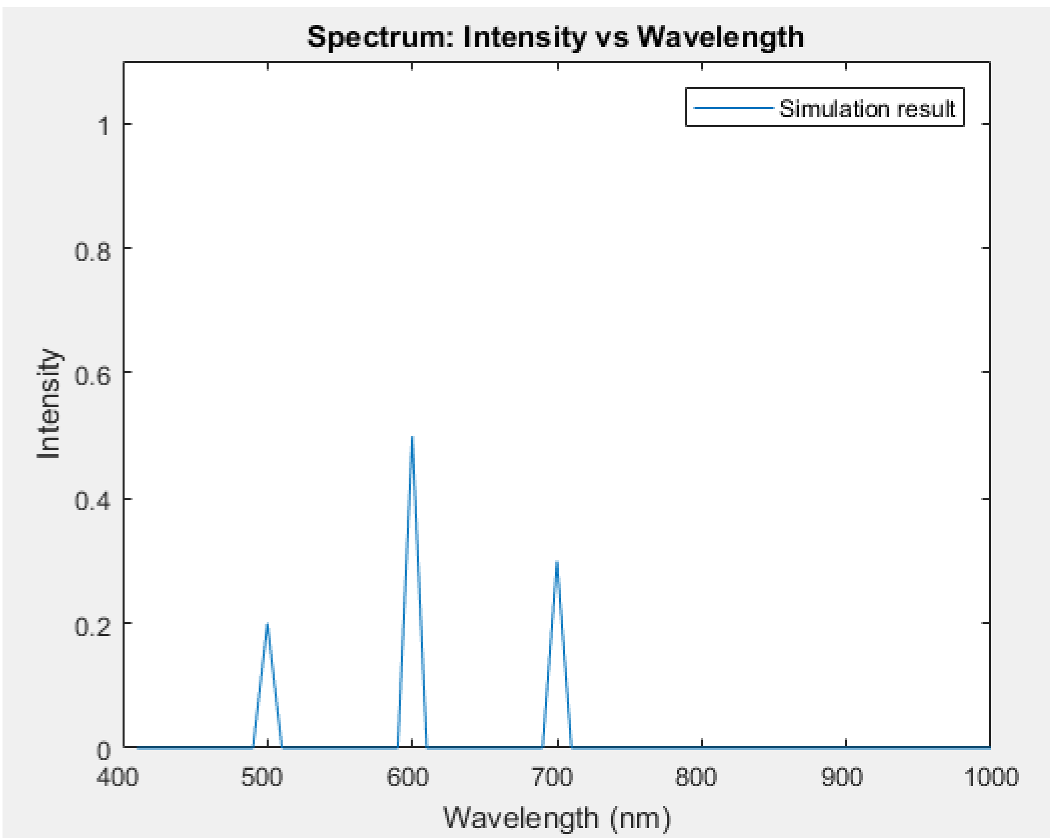

Fig. 8 Simulated Intensity vs Wavelength spectrum plot in MATLAB

3.2 DESIGN OF THE COMPACT SPECTROMETER

The design of the compact spectrometer can be simply illustrated in **Fig. 10**. There is a convex lens (**Fig. 10 (b)**) helping the laser light shine on the whole cylindrical lens (**Fig. 10 (d)**). The line-shaped beam converted by the cylindrical lens is then focused by another convex lens (**Fig. 10 (e)**). At the focus point, there would be a thin film (See **Fig. 9**) placed for producing the thin film interference, which is recorded by the CMOS camera. Moreover, the mechanism of detecting the input signal's spectrum can be found in section 3.1 (especially in **Fig. 7**). The range of θ in **Fig. 7** is determined by the inverse tangent of the ratio between the convex lens' radius (0.5 inches) and focal length (1 inch). Therefore, the range of θ is from 0 degree to around 26.6 degree.

Fig. 9 The thin film purchased from Thorlabs [5]

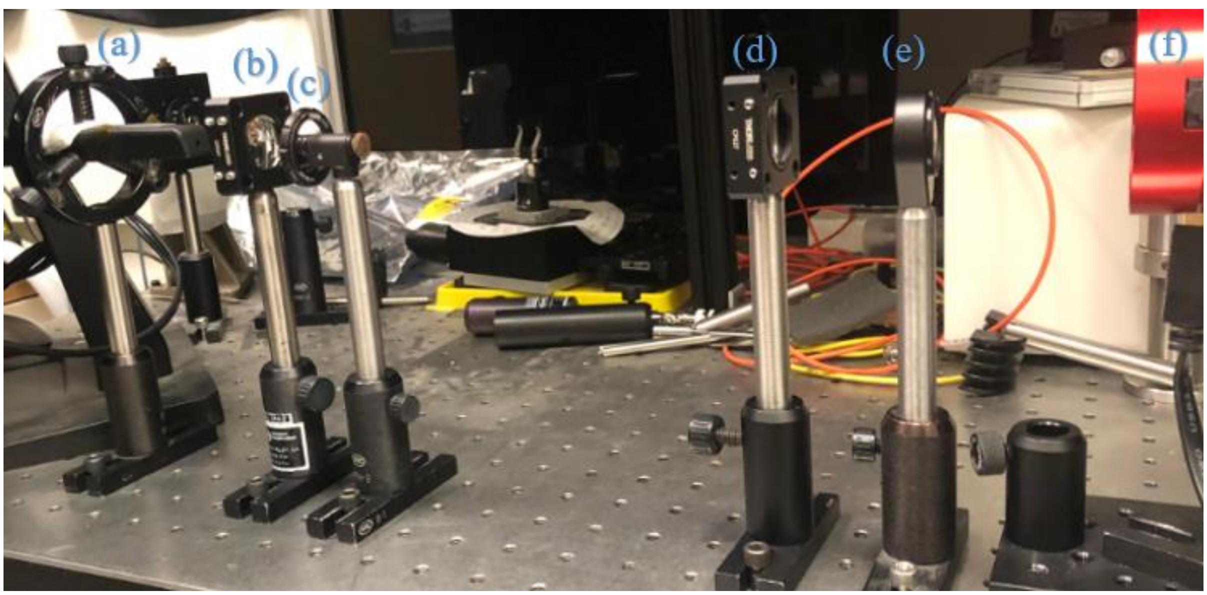

Fig. 10 The setup of the compact spectrometer. From left to right: (a) red light laser pointer; (b) convex lens; (c) optical filter; (d) cylindrical lens; (e) convex lens; (f) CMOS camera

3.3 TRANSMISSION MATRIX MEASUREMENT

For knowing the transmission matrix of the thin film, an experimental measurement of the thin film’s transmission coefficients under different wavelengths. For the factor of the incident angle, since the input light passes through the convex lens, there are beams from different incident angles shine on the thin film. By selecting a vertical line on the recorded image from the CMOS camera, the transmission coefficients at different points on the line present the results from different incident angles (**See Fig. 7 (d)**).

For getting a tunable light source, monochromator can be used. Because of the time-consuming issue, a red light laser point with around 650 nm wavelength is used to conduct a preliminary measurement. The result is shown in **Fig. 11**. By reducing the noise and smoothing the plot in **Fig. 11 (c)**, the moving-average filter is applied and the window size of the filter is chosen as 160. The result by applying the filter is illustrated in **Fig. 11 (d)**. From the result, the region between 900th pixel and 1500th pixel is shown to experience the change of transmission coefficient, which happens in the region between 10 to 25 degree in the simulation result (See **Fig. 11 (a)**).

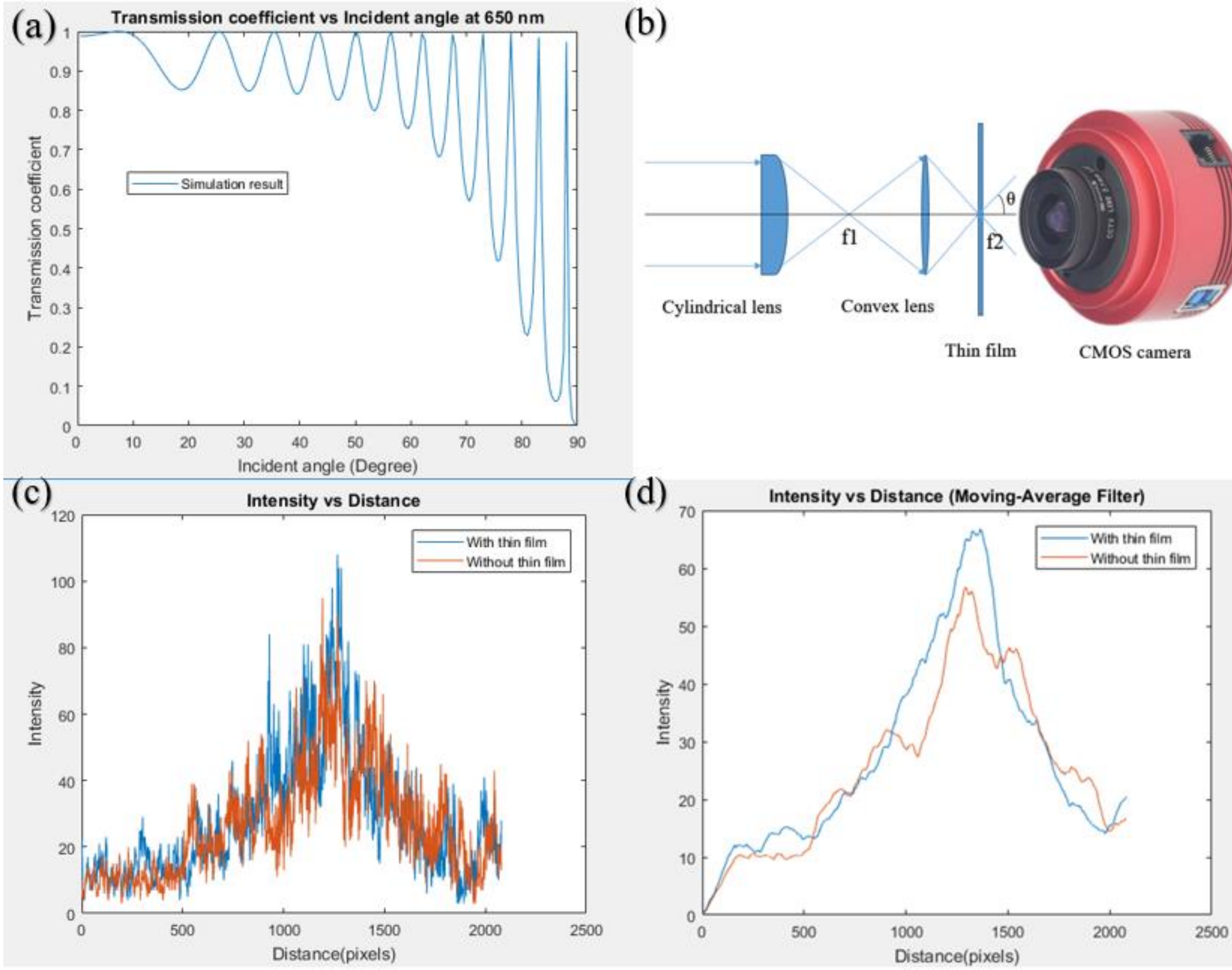

Fig. 11 The preliminary result: (a) Calculated relationship between transmission coefficient and incident angle of the thin film interference for an incident light beam with wavelength of 650 nm; (b) The schema diagram illustrates how the CMOS camera captures images of the thin film interference by using a cylindrical lens and a convex lens; (c) Comparison between the captured image using a thin film and that without a thin film by importing both images into MATLAB. The maximum intensity the CMOS camera can detect is 255; (d) Image processing for the plot from (c) by using Moving-Average filter in MATLAB.

CHAPTER 4. CONCLUSION

The approach of using thin film interference has a great potential to create a low- price and high performance compact spectrometer. By knowing the transmission matrix of the thin film and using the data from the recorded images by a CMOS camera, the spectrum of the optical input signal can be calculated easily. The difficulty of this project is the measurement of the transmission matrix of the thin film. The results of the measurement needs to be very accurate. And the measurement environment needs to be improved to reduce the noise in the results. In the future, a cover or shield should be designed to protect and stabilize the components of the compact spectrometer; and it could be manufactured by 3D printing.

REFERENCES

[1] Liu, Z. (n.d.). A Mobile G-Fresnel based Spectrometer. Retrieved March 21, 2019, from http://ultrafastoptics.ee.psu.edu/mobile_spectrometer/

[2] Bell, P. (n.d.). Prism Spectrometer [PowerPoint slides]. Retrieved March 21, 2019, from https://slideplayer.com/slide/9337231/

[3] Thin Film Interference. (n.d.). Retrieved March 21, 2019, from https://sciencedemonstrations.fas.harvard.edu/presentations/thin-film-interference

[4] Guldin, S., Optical Aspects of Thin Films and Interfaces, in Inorganic Nanoarchitectures by Organic Self-Assembly. 2013, Springer.

[5] Thorlabs. (n.d.). [Product Raw Data: Pellicle Beamsplitters, Uncoated for 8:92 (R:T), 400 - 2400 nm]. Unpublished raw data.