Prototypical Simulation of an Optical Edge Filter Design for Three Different Rayleigh Wavelengths Using Octave Software

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Optical filters used specifically for special functions to block a particular wavelength or range of wavelength and transmit the rest of the spectrum have received research attention for the past few eras. Recently, optical filter based on multilayer coating are more focused due to potential to manipulate filter properties by changing layer thickness in order to apply in various fields. This Quarter wave stack (QWS) model design is one of the approaches to design optical filter such as edge filter. However, to obtain desire minimum specification need an optimization. Therefore, in this study aims to design optical edge filter based QWS model by optical matrix method in Octave software. In this design, MoS\textsubscript{2} and Si are being choose for high (H) and low (L) refractive index materials respectively. The optimum twenty-four (24) number of layers are determined by calculating maximum transmittance obtained. The Rayleigh wavelength (\(\lambda_{ex}\)) of 405 nm ,532 nm and 633 nm are selected and ‘glass|12HL|air’ configuration is set for the design simulation. Then, the cut-on wavelength (\(\lambda_{cut-on}\)) and cut-off wavelength (\(\lambda_{cut-off}\)) of successful designed optical edge filter are measured. The result shows that the cut-on wavelength of 408.11 nm, 536 nm and

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640.25 nm with minimum effective transmission (MET) of 32.3%, 31.3% and 32% respectively are obtained. In conclusion, this present study shows the deviation between the calculated value and simulation of about 0.2 nm, 1.7 nm and 1.15 nm for each $\lambda_{ex}$ of 405 nm, 532 nm and 633 nm is determined. But for $\lambda_{cut-off}$, the value obtained are much higher than the calculated value. The MET of each filter is 32.3%, 31.3% and 32% for Rayleigh wavelength respectively.

Keywords: Optical filter; cut-on wavelength; minimum effective transmission.

1. INTRODUCTION

In the present era, optical filters have gained a renewed interest due to their increasing demand for various applications such as analytical instrument, florescence, microscope, Raman spectrometer, clinical chemistry, or machine vision inspection. These devices are accessible in the market such as band pass filter, high pass filter, low pass filter, and band stop filter [1-3].

An optical filter can be designed in two different ways, first by using the properties of the deposited materials to absorb light of a given wavelength this is termed as absorption filter [4], but this types of filter can be easily damage by heat. The second method of design is using the interference effect of light. This method of design filter is an ideal kind of thin film filter that provides the designer with a wide range of design parameter to produce the require characteristic [5]. The basic types of interference filter consist of a stack of high and low refractive index materials each of one quarter (1/4) wavelength thickness. However, the performance of this types of an optical filter depends on the number of layers, their thickness, and refractive index difference between the layers [1,6].

Multilayer thin film (MTF) filter combines attractive properties of several materials. Moreover, MTF filters play a momentous role to offer the highest standard such as enhancements in transmission, reflection, blocking, and either transmitted or reflected wave front properties. It is included of a sequence of boundaries sandwiched between different materials to form a thin film [7]. Hence, MTF can be used for many applications such as computer disk, optical filter, anti-reflector, solar cells, and in telecommunication industries [8].

MTF filter based on Quarter-wave stack (QWS) model is one the most important method in assemble optical filter that consists of multiple alternative layers of high and lower dielectric materials. QWS model is a basic building block for thin-film filters which made up of alternating of high and low index materials. Each one quarter (1/4) of an optical wavelength in thickness, the light of a specific wavelength is very strongly reflected. The additional benefit of using quarter wave stack is that it is materials independent and straight forward than other methods [5].

Generally, MTF filter based QWS model has been fabricated for many years using different methods such as spray pyrolysis [9], radio frequency (RF) magnetron sputtering [10], thermal evaporation [9], and sol-gel [11]. Design this optical filter using simulation will give the exact thickness, the number of layers, cut-on/cut-off wavelength and minimum transmission. In this present work, Octave software is used to simulate a computer program for MTF filter design. The aforementioned software has advantage over other due easy to usage, built-in support of a complex number, and extensibility in form of a user-defined function [12].

2. QUARTER-WAVE STACK

Quarter-Wave is one of the fundamental building blocks of thin film filters. It comprises periodic stacks of layers of thickness alternating layer of H and L refractive index (M A Butt et al., 2017). These filters used in various ways such as long pass filter (LWP), a short pass filter (SWP) and band stop filter [13]. It is also used in a direct high reflectance coating for example laser mirror.

3. EFFECT OF NUMBER OF LAYERS IN DESIGN OPTICAL FILTER

Thin film optical structure comprises of many layers of contrasts materials with different refractive index and are arranged based on high (H) and low (L) index. The layers are in the range of friction of nanometer (nm) to micrometer (μm) in thickness. The filter design can be arranging in a stack (Vaida, Birdeanu, & Birdeanu, 2019) as follows:

Air |HLHLH|HLHLH|HLHLH|HLHLH|Glass

In multilayer optical filter design, the number of the layer has a great impact on reflectance and
transmittance. This means the reflectance or transmittance can either increase or decrease by just increases the number of layers [14,15].

4. EQUATIONS FOR MULTILAYER THIN FILM (MTF) ASSEMBLY OPTICAL FILTER DESIGN

The subsequent matrix can be used to estimate optical properties, of nth layers. This means that each layer generates a matrix in the equations which will change the electric and magnetic field. The final result is related to the admittance of the incidence medium the surface of the admittance of the thin film and substrate to obtain the coefficient of reflectance or transmittance [5-6].

\[
\begin{bmatrix}
E \\
H
\end{bmatrix} = M \begin{bmatrix} 1 \\ \eta_s \end{bmatrix}
\]

(1)

\[
\begin{bmatrix}
E_o \\
H_o
\end{bmatrix} = \begin{bmatrix}
\cos \delta & \sin \delta/\eta_s \\
-\sin \delta/\eta_s & \cos \delta
\end{bmatrix} \begin{bmatrix}
E_1 \\
H_1
\end{bmatrix}
\]

(2)

\[
M_r = \begin{bmatrix} 1 \\ \eta_s \end{bmatrix} \begin{bmatrix}
\cos \delta & i/\eta_s \sin \delta \\
-\eta_s \sin \delta & \cos \delta
\end{bmatrix}
\]

(3)

\[
M = M_1 M_{L-1} \ldots M_r M_2 M_r \ldots M_{2M-1}
\]

(4)

Where M is 2 x 2 matrix represents the rth thin film of the system.

The above matrix is equal to

where \([B/C]\) is define as the characteristic matrix assembly

\[B(E) = \text{normalized electric field at the front interface}\]

\[C(H) = \text{normalized magnetic field at the front interface}\]

But phase \((\delta r)\) of the wave inside layer is given by

\[
\delta r = \frac{2\pi}{\lambda} \sin \delta \phi = 2\pi/\lambda \sin \delta \phi
\]

\[
\delta_r = \left( \frac{2\pi}{\lambda} \right) d_r (n_r^2 - k_r^2 - n_s^2 \cos^2 \theta - 2 \sin \theta \cos \theta)^{1/2}
\]

(5)

\[
\eta_p = \frac{n}{\cos \phi} \text{ for P- polarization}
\]

(6)

\[
\eta_s = n \cos \phi \text{ for S- polarization}
\]

(7)

And also

\[
\rho = \left[\eta_o - \eta_i\right] \left[\eta_o - \eta_i\right]^* \text{ but } \eta \text{ is admittance of multilayer thin film}
\]

\[
Y = \frac{\eta_o \cos \delta + \eta_s \sin \delta}{\cos \delta + i(\eta_s/\eta_o) \sin \delta}
\]

(8)

\[
R = \rho^* = \rho \rho^* \text{ for \(405 \text{ nm}\), the amplitude of the reflectance coefficient is representing by } \rho
\]

(9)

\[
T = \frac{4\pi \Re(\eta)}{(\eta + 1)/(\eta + 1)}
\]

(10)

5. RESULTS AND DISCUSSION

Three different edge filters of \(\lambda_o\) of 405 nm, 532 nm, and 633 nm have been simulated for wavelength between 300-1000 nm using different \(\lambda_o\). The result obtained is divided into three different cases i.e. Case I, Case II and Case III respectively. In each case, the reflectance, transmittance against wavelength are plotted using and equal number of layers are obtained Raman shift

\[
\text{cm}^{-1} = \frac{10^7}{\lambda(\text{nm})} - \frac{10^7}{\lambda(\text{nm})} \times 10^7/\lambda(\text{nm})
\]

(11)

5.1 Case I: Edge Filter of Rayleigh Wavelength (\(\lambda_{ex}\) 405 nm

Table 2 shows the thickness of MoS2 and Si materials obtained from the simulation and the arrangement of layer on a glass substrate. Fig. 3 shows graphs of reflectance and transmittance

| S/N | \(\lambda_{ex}\) (nm) | Target \(\lambda_{cut-on}\) (nm) corresponds to 200 cm\(^{-1}\) Raman shifts. | Target \(\lambda_{cut-off}\) (nm) corresponds to 4000 cm\(^{-1}\) Raman shifts |
|-----|----------------------|-------------------------------------------------|-------------------------------------------------|
| 1   | 405                  | 408.31                                          | 483.29                                          |
| 2   | 532                  | 537.70                                          | 675.81                                          |
| 3   | 633                  | 641.10                                          | 847.67                                          |
### Table 2. Calculated thickness of individual layer of MoS$_2$ and Si for filter correspond to $\lambda_{ex}$ = 405 nm

| Number of layers | Materials | Thickness (nm) |
|------------------|-----------|----------------|
| Air              | Si        | 32.64          |
| 24               | Si        | 32.64          |
| 23               | MoS$_2$   | 21.54          |
| 2                | Si        | 32.64          |
| 1                | MoS$_2$   | 21.54          |
| Substrate        |           |                |

**Fig. 1.** Reflectance and transmittance against $\lambda$ for $\lambda_{ex}$ = 405 nm
against $\lambda$ or MTF edge filter. The result shows 100% reflectance with high distortion at the right-hand side with $\lambda_{\text{cut-on}}$ and $\lambda_{\text{cut-off}}$ of 408.11 nm and 700 nm are obtained. The result show that the MET of the filter is 33%.

5.2 Case II: Edge Filter of Rayleigh Wavelength ($\lambda_{\text{ex}}$) of 532 nm

The thickness of each layer arrangement is shown in Table 3 on a glass substrate. Fig. 2 shows the graph of reflectance and transmittance against $\lambda$ of the edge filter for $\lambda_{\text{ex}} = 532$ nm, with $\lambda_{\text{cut-on}} = 536$ nm and $\lambda_{\text{cut-off}} = 800$ nm. The result show that the MET of the filter is 31.3%.

5.3 Case III: Edge Filter of Rayleigh Wavelength ($\lambda_{\text{ex}}$) of 633 nm

Table 4 also shows the thickness of each layer using the same materials and the same numbers of layers as previously stated. Fig. 3. Therefore, edge filter of $\lambda_{\text{ex}} = 633$ nm with $\lambda_{\text{cut-on}}$ and $\lambda_{\text{cut-off}}$ of 640.25 nm and 1000 nm are obtained. The result show that the MET of the filter is 32%.
Table 3. Calculated thickness of individual layer of MoS\(_2\) and Si for filter correspond to \(\lambda_{ex} = 532\) nm

| Number of layers | Materials | Thickness (nm) |
|------------------|-----------|----------------|
| Air              | Si        | 36.93          |
| 24               | Si        | 36.93          |
| 23               | MoS\(_2\) | 27.34          |
| 2                | MoS\(_2\) | 27.34          |
| 1                | MoS\(_2\) | 27.34          |
| Substrate        |           |                |

Table 4. Show layer thickness of 633 nm edge filter

| Number of layers | Materials | Thickness (nm) |
|------------------|-----------|----------------|
| Air              | Si        | 49.61          |
| 24               | Si        | 49.61          |
| 23               | MoS\(_2\) | 34.50          |
| 2                | Si        | 49.61          |
| 1                | MoS\(_2\) | 34.50          |
| Substrate        |           |                |

Table 5. Show \(\lambda_{cut-on}\) and \(\lambda_{cut-off}\) edge filter \(\lambda_{ex} 405\) nm, 532 nm and 633 nm

| S/N | \(\lambda_{ex}\) (nm) | \(\lambda_{cut-on}\) (nm) | \(\lambda_{cut-off}\) (nm) |
|-----|-----------------------|---------------------------|---------------------------|
| 1   | 405                   | 408.11                    | 700.00                    |
| 2   | 532                   | 540.00                    | 800.00                    |
| 3   | 633                   | 640.25                    | 1000.00                   |

Three different edge filters are successfully simulated and the \(\lambda_{cut-on}\) and \(\lambda_{cut-off}\) each filter

Fig. 3. Reflection and transmittance against \(\lambda\) for \(\lambda_{ex} = 633\) nm

![Graph showing reflection and transmittance against wavelength for \(\lambda_{ex} = 633\) nm]
are obtained. Table 5 summarized the result obtained from three different filter.

6. CONCLUSION

In conclusion, the differences between $\lambda_{\text{cut-on}}$ and $\lambda_{\text{cut-off}}$ were calculated using Raman shift equation and simulated in octave software are very small was observed. The deviation between them about 0.2 nm, 1.7 nm and 1.15 nm for each $\lambda_{\text{ex}}$ of 405 nm, 532 nm and 633 nm is determined. But for $\lambda_{\text{cut-off}}$, the value obtained are much higher than the calculated value. The MET of each filter is 32.3%, 31.3% and 32% for 405 nm, 532 nm and 633 nm $\lambda_{\text{ex}}$ respectively.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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