Australian Journal of Basic and Applied Sciences, 11(11) August 2017, Pages: 186-193

AUSTRALIAN JOURNAL OF BASIC AND APPLIED SCIENCES

ISSN:1991-8178 EISSN: 2309-8414
Journal home page: www.ajbasweb.com

Modeling of High Performance Reflection Coatings for Visible Region

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ARTICLE INFO

Article history:
Received 18 June 2017
Accepted 28 July 2017
Available online 20 August 2017

Keywords:
thin films, modeling, reflection coating, optical filters.

ABSTRACT

Background: Optical coating is a process of deposit one or more thin films of materials on optical components such as mirrors or lenses, which changes the way in which the optical components reflect or transmit light. **Objective:** This paper aims to study high reflection coatings for visible region (400-800nm) which designed using the optical matrix approach method. MATLAB program version 8.1 was used to model the designs. **Result:** The reflection of a glass substrate of refractive index $n_s = 1.5$ was enhanced by adding successive dielectric layers of alternating high refractive index $(n_H = 2.42)$ from TiO_2 material with geometrical thickness $(d_H = 65.818\,nm)$ and low refractive index $(n_L = 1.38)$ from MgF_2 material with geometrical thickness $(d_L = 99.637nm)$ respectively. Firstly, the reflectance increased to (41.43%) by the suggested design (glass |LH| air), then the reflectance rapidly increased when the number of periods increased to reach (R=75.39% and R=97.06%) for the designs (glass $|LH|^2$ air) and (glass $|LH|^4$ air) respectively. Finally, the maximum reflectance achieved by adding twelve layers depending on the design (glass $|LH|^6$ air), the reflectance reached the value (R=99.69%) at central wavelength 550nm. **Conclusions:** The reflectance of the glass increased by increasing the number of layers and the high reflectance achieved by putting the layer of high refractive index as outer layer. It is observed that the width of the reflectance does not affected by increasing the number of layers.

INTRODUCTION

Reflective optical coatings have been widely used in many applications including mirrors, lenses, lasers, IR diodes, and optical filter (Pedrotti, 1987). Highly reflecting dielectric mirrors have been developed to be used in Laser Resonator, Space Telescopes, Satellites, and in Fabry-Perot interferometers (Macleod, 2010; Netterfield *et al*, 1980). Visible waves are electromagnetic waves with frequencies lower thanultravioletwaves, the wavelengths ranging from 400 to 700nm. High Reflectance Mirrors are designed from a thin layer of metal material (Eckertova, 1977). A number of layers are deposited on the substrate from dielectric materials or a mixture of insulating and metal materials by choosing the appropriate refractive index and optical thickness for each layer and number of layer (Li, 1985; Yoldas and T. O'Keefe, 1984). The optical performance of themultilayer system can be determined by appropriate choosing of absorption coefficient, and geometrical thickness of each layer and coefficients of the refraction of the surrounding including Incident Medium, and substrate (Arora and Hauser, 1982; Nagendra *et al*, 1985). Optical performance is defined as Reflectance (R), Transmittance (T), and Absorption (A) as a function of the wavelength or frequency for the optical beam.The electromagnetic wave is incident on thelayer surface bonding two substances of indices $n_\circ$andn_s, the wavesuffers absorption, reflection, and transmittance, according to Equation (1), the interference pattern will be supported by the film as shown in Figure. 1 (Abed and Turki, 2013).

$$R + T + A = 1 \quad (1)$$

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To Cite This Article: Sabah Ibrahim Abbas, Salman Rasool Salman, Shaymaa Saadoon Hashim., Modeling of High Performance Reflection Coatings for Visible Region. ***Aust. J. Basic & Appl. Sci.,*** *11(11): 186-193, 2017*

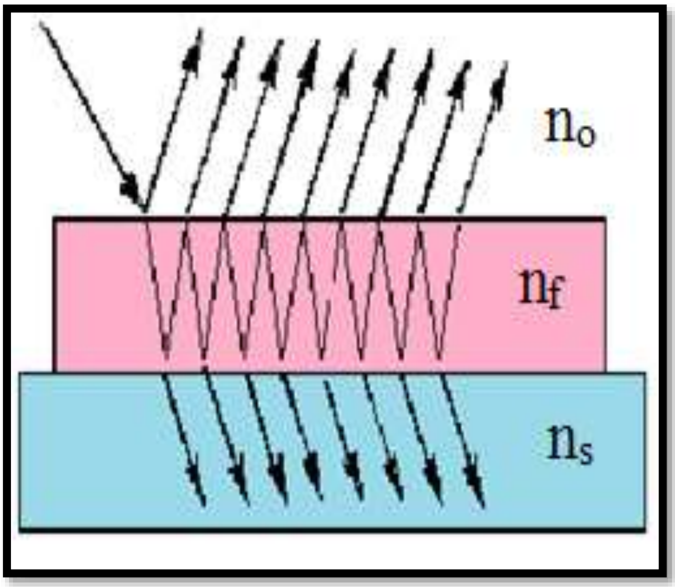

Fig. 1: Thereflectance and transmittance rays by a single layer with refractive index n_f.

Increasing or decreasing of the reflectance beam is depending on the constructive or destructive interference respectively; when the reflectance beam from the film surface has the same phase causes the constructive interference (Genkins and White, 1981). Most optical coatings have more than one layer, the interference calculations in such cases can be very complicated because there are many more light rays involved due to the reflection backs and forth between various interfacesas shown in Figure. 2. It is possible to organize the layers to produce a desired interference effect and thus to create optical coatings because quarter-waves and half-waves represent extreme interference conditions (Macleod, 1986).

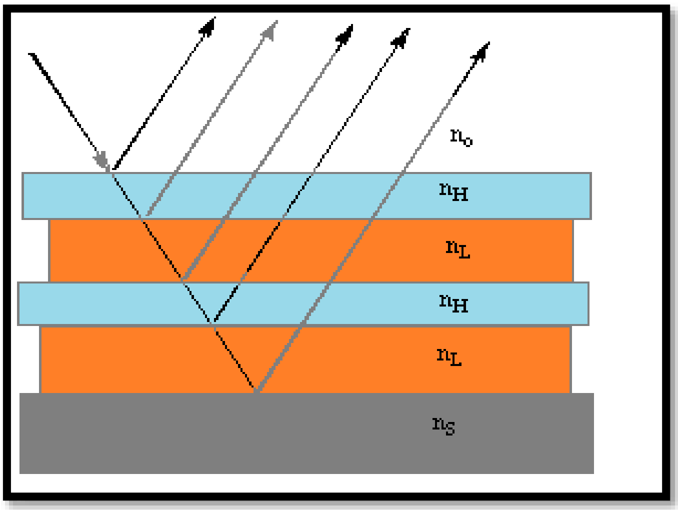

Fig. 2: Multilayer stacks of thin films with high refractiveindex n_H and low refractive index n_L each film has an optical thickness of $\frac{\lambda_\circ}{4}$.

This research presents the design, simulation, and characterization of multilayer high reflection thin films composed of titanium dioxide TiO_2withrefractive index (2.346) and magnesium fluoride $MgF_2$with refractive index (1.38) on the glass substrate (Mohammad, 2013; Abdalgadda *et al*, 2016).

2. Theory:

Interference of light in a thin film can be explained by the wave theory of light. When a light wave traveling in a certain medium having refractive index $n_\circ$, and incident on a medium having different refractive index n_f, a portion of light reflects at the interface as shown in figure.3. The amplitude of this reflected light wave which is equivalent to the electric field strength depends on the refractive index of a medium at the interface. This assumption was developed by Jean Fresnel in 1896 (Pedrotti, 1987).

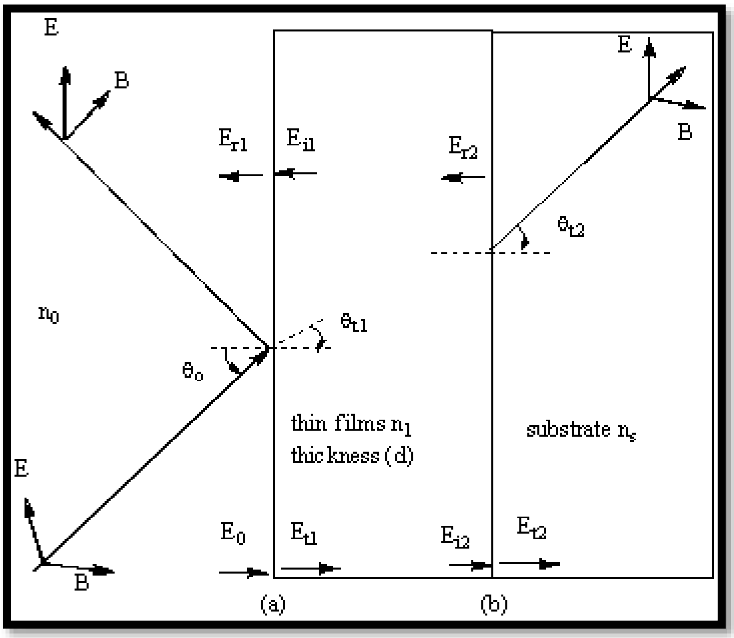

Fig. 3: Electromagnetic waves propagation through a thin film.

An electromagnetic wave can be represented by equations:

$$\vec{E}= E_{\circ} e^{I(wt-nk.r)} \quad (2)$$

$$\vec{H} = H_{\circ} e^{i(wt-nk.r)} \quad (3)$$

Where $\vec{E}$ and $\vec{H}$ are electric and magnetic fields respectively, k is the wave number, ω is the angular frequency and n is the refractive index of the propagation medium (Ghasemi, 2013). Nonmagnetic, isotropic, and homogeneous dielectric thin film of refractive index n_1 deposited on the glass substrate. Where $E_{\circ}$is the incident field, E_{r1} is the reflected field and $E_{t1}$is the transmitted electric field. According to the boundary conditions, the tangential components of the resultant electric andmagnetic fields are continuous across the interface of the film.

$$E_a = E_{\circ} + E_{r1} = E_{t1} + E_{i1} \quad (4)$$
$$E_b = E_{i2} + E_{r2} = E_{t2} \quad (5)$$
$$B_a = B_{\circ} cos\theta_{\circ} - B_{r1}\, cos\theta_{\circ} = B_{t1} cos\theta_{t1} - B_{i1}\, cos\theta_{t1} \quad (6)$$
$$B_b = B_{i2} cos\theta_{t1} - B_{r2}\, cos\theta_{t1} = B_{t2}\, cos\theta_{t2} \quad (7)$$

The magnetic field can be expressed as a function of the electric field:

$$B = \frac{n}{c} E \quad (8)$$
$$B_a = \left(\frac{n_{\circ}\, cos\theta_{\circ}}{c}\right)(E_{\circ} - E_{r1}) = \alpha_{\circ}(E_{\circ} - E_{r1}) = \alpha_1\,(E_{t1} - E_{i1}\,) \quad (9)$$
$$B_b = \left(\frac{n_1\, cos\theta_{t1}}{c}\right)(E_{i2} - E_{r2}) = \left(\frac{n_s \cos\theta_{t2}}{c}\right)E_{t2} = \alpha_1(E_{i2} - E_{r2}) = \alpha_s\, E_{t2} \quad (10)$$

There is a phase difference between E_{i2} and E_{t1} is given by equation:

$$\delta = \left(\frac{2\pi}{\lambda_{\circ}}\right) n_1 d\, cos\theta_{t1} \quad (11)$$

The electric field can be expressed in phase difference:

$$E_{i2} = E_{t1}e^{-i\delta}\text{And}E_{i1} = E_{r2}e^{-i\delta} \quad (12)$$

By using the boundary condition,these conditions state that the two components of E and B parallel to the interface must havethe same value in both sides, yields.

$$E_b = E_{t1}e^{-i\delta} + E_{i1}e^{i\delta} = E_{t2} \quad (13)$$
$$B_b = \alpha_1\left(E_{t1}e^{-i\delta} - E_{i1}e^{i\delta}\right) = \alpha_s E_{t2} \quad (14)$$

The two electric fields E_{t1} and E_{i1} can be expressed in terms E_b, B_b:

$$E_{t1} = \left(\frac{\alpha_1 E_b + B_b}{2\alpha_1}\right)e^{i\delta} \quad (15)$$
$$E_{i1} = \left(\frac{\alpha_1 E_b - B_b}{2\alpha_1}\right)e^{-i\delta} \quad (16)$$

Substituting the two equation (15), (16) in the initial electric and magnetic field components representing by equations (4) to (7), obtain.

$$E_a = E_b \cos\delta + B_b\left(\frac{i\sin\delta}{\alpha_1}\right) \quad (17)$$
$$B_a = E_b(i\alpha_1 \sin\delta) + B_b\cos\delta \quad (18)$$

These equations relate the electric and magnetic fields components at the first boundary to those at the next one and can be written in matrix form (Macleod, 1986).

$$\begin{pmatrix} E_a \\ B_a \end{pmatrix} = \begin{pmatrix} \cos\delta & \frac{i\sin\delta}{\alpha_1} \\ i\,\alpha_1\,\sin\delta & \cos\delta \end{pmatrix}\begin{pmatrix} E_1 \\ B_1 \end{pmatrix} \quad (19)$$

Rewrite the equation (19) in therefractive index term of a single layer $n_1$deposited on substrate with a refractive index $n_s$is represented as follows (Medhat *et al*, 2016):

$$\begin{bmatrix} B \\ C \end{bmatrix} = \begin{bmatrix} \cos\delta_1 & \frac{(i\sin\delta_1)}{n_1} \\ n_1(isin\,\delta_1) & \cos\delta_1 \end{bmatrix}\begin{bmatrix} 1 \\ n_s \end{bmatrix} \quad (20)$$

The phase thickness of the film ($\delta_1 = \frac{2\pi\, n_1\, d_1\, \sin\theta_1}{\lambda_\circ}$), where d_1 the geometric thickness of the film and $\lambda_\circ$ is the monitoring wavelength, θ_1 is the angle of propagation wave through the film. The characteristic matrix was employed tocalculate the reflectance of N layers design of thin films (Macleod, 2010).

$$\begin{bmatrix} B \\ C \end{bmatrix} = \left(\prod_{J=1}^{N}\begin{bmatrix} \cos\delta_J & \frac{(isin\,\delta_J)}{n_J} \\ in_J\, sin\delta_J & \cos\delta_J \end{bmatrix}\right)\begin{bmatrix} 1 \\ n_s \end{bmatrix} \quad (21)$$

Where *B* and *C* is total electric and magnetic field amplitudes of the light propagating in the medium.Thus optical admittance is given by the ratio

$$Y = \frac{C}{B} \quad (22)$$

The reflectance R, absorbance A, and phase difference φ of a stack of non-absorbing, optically homogeneous films deposited upon a transparent substrate are a function of the geometrical thicknessare given by equations:

$$R = \left(\frac{n_\circ - Y}{n_\circ + Y}\right)\left(\frac{n_\circ - Y}{n_\circ + Y}\right)^* \quad (23)$$
$$A = \frac{4n_\circ\, Re\,(BC^* - n_s}{(n_\circ + Y)(\,n_\circ + Y)^*} \quad (24)$$

When the light falls from a less intense optical medium such as the air to a denser optical medium such as the glass, the incident light suffers a reversalin phase because of reflection. The change in phase depends on the type of reflection if it is an external reflection or an internal reflection. The phase change is given by equation (Macleod, 2010).

$$\varphi = tan^{-1}\left(\frac{in_\circ\,(\,CB^* - BC^*}{(\,n_\circ^2\,BB^* - CC^*)}\right) \quad (25)$$

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RESULT AND DISCUSSION

Enhancement the optical parameter (reflectance) of the glass substrate in the visible region at the monitoring wavelength 550 nm by choosing the optimum materials has the transparent properties in the visible region. To increasing thereflectivity and reduces the absorptance a multilayer dielectric thin film is utilized in general because the absorptionin metal layers is very high and their reflectance very low. Where the large number ofsuccessivereflections magnifies the effects of absorption, optical systems with high power, where the energy absorbed can be sufficient to damage the coating.The high reflectance coating consisting of a stack of quarter wave dielectric layers of alternating high refractive index $(n_H = 2.42)$ from TiO_2 material with geometrical thickness $(d_H = 65.818\, nm)$ and low refractive index $(n_L = 1.38)$ from MgF_2material with geometrical thickness $(d_L = 99.637 nm)$respectively. All these layers deposited on the glass substrate with refractive index (n_s =1.50), previous equations have been programmed by MATLAB program version 8.1, to design the performance of the high reflectance coating atcentral wavelength$\lambda_\circ = 550\, nm$ for normal incident of the light.The stack is consisting of alternate layers of identical highindex and lowindex films. Eachfilm has an optical thickness of$(n_H d_H = n_L d_L = \frac{\lambda_\circ}{4})$, a little analysis shows that all emerging beams are in the same phase. Multiple reflections in the light band of design wavelength$\lambda_\circ$ increase the total reflected intensity and thequarter-wave stack performs as an efficient mirror.The reflectance from the glass substrate surface is 4% as shown in figure .4.The amount of light reflected is known as reflection loss and the reflectance of the glass substrate is stayed constant in the visible region of light for this reason the transmittance of glass has too high 96%. Light has reflected both sides when going from air to the glass and at the otherside when going from glass back to air, the size of the loss is the same in both cases.

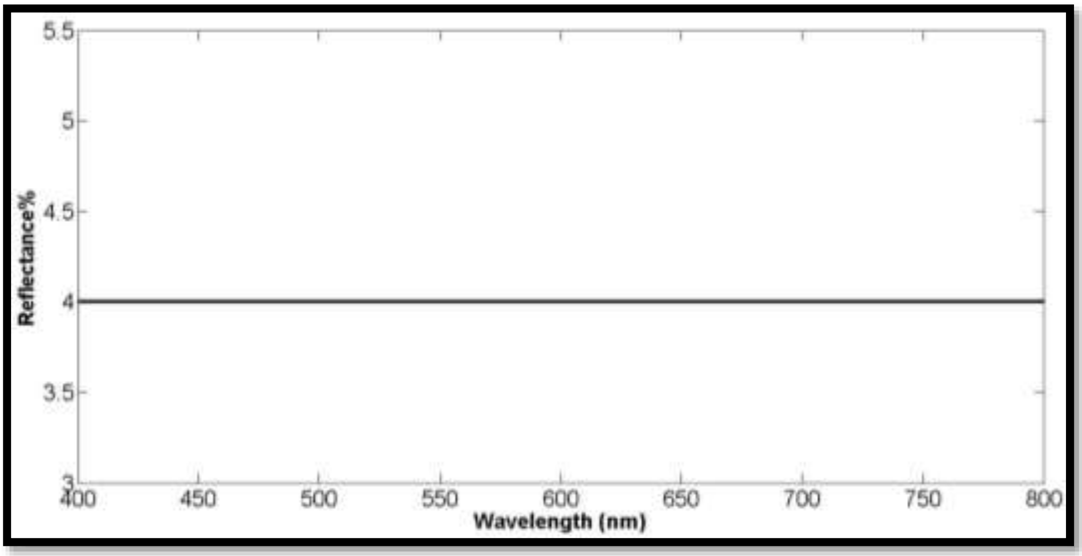

Fig. 4: Reflectance of the glass substrate.

We suggested the following design (glass |LH| air) to increase the reflectance of the glass substrate where the thickness of each layer is a quarter wave lengths. The magnitude of the reflectance is increases to (41.43%) when placing a material of high refractive index material (TiO_2) as an outer layer

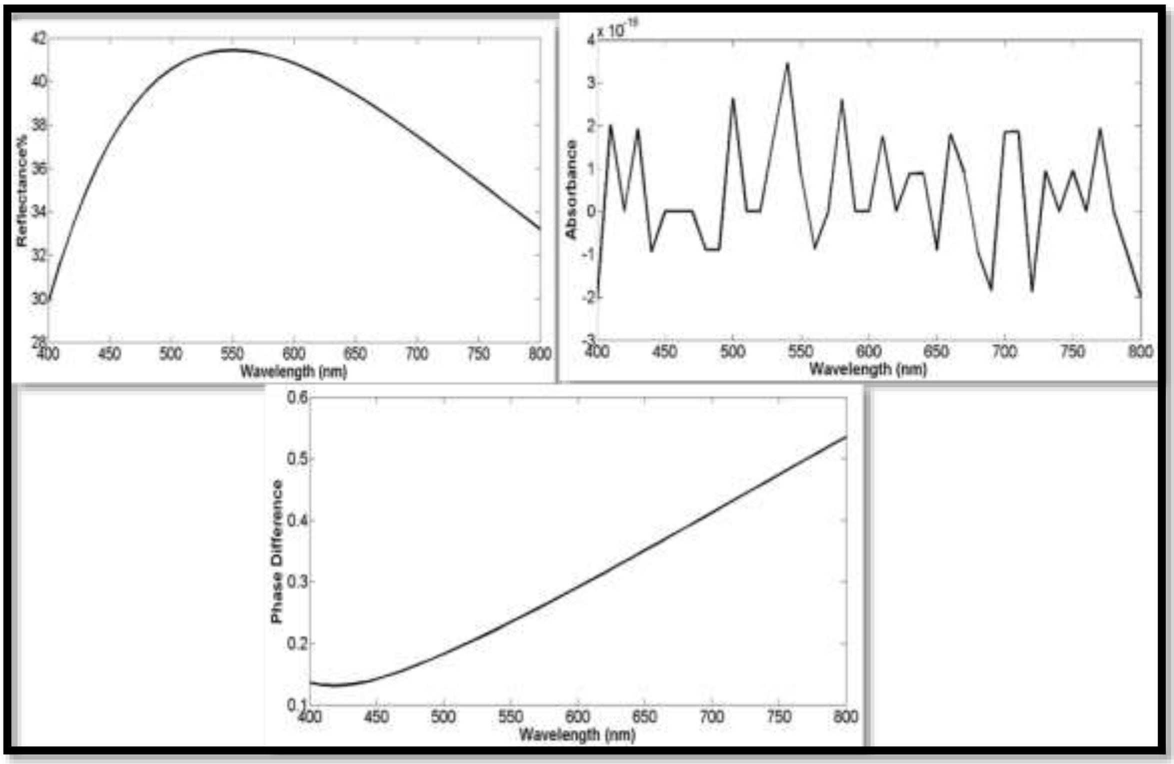

Fig. 5: Reflectance, Absorbance, and Phase Difference for the design (glass |LH| air).

Figures (6 and 7) shows the reflectance rapidly increaseswhen the number of periods increases to reach (R=75.39% and R=97.06%) for designs (glass|LH|^2 air) and (glass|LH|^4 air) respectively. The addition of two layers periodicallyreduces the transmittance by a factor depends on the ratio of two layers low to high refractive index.

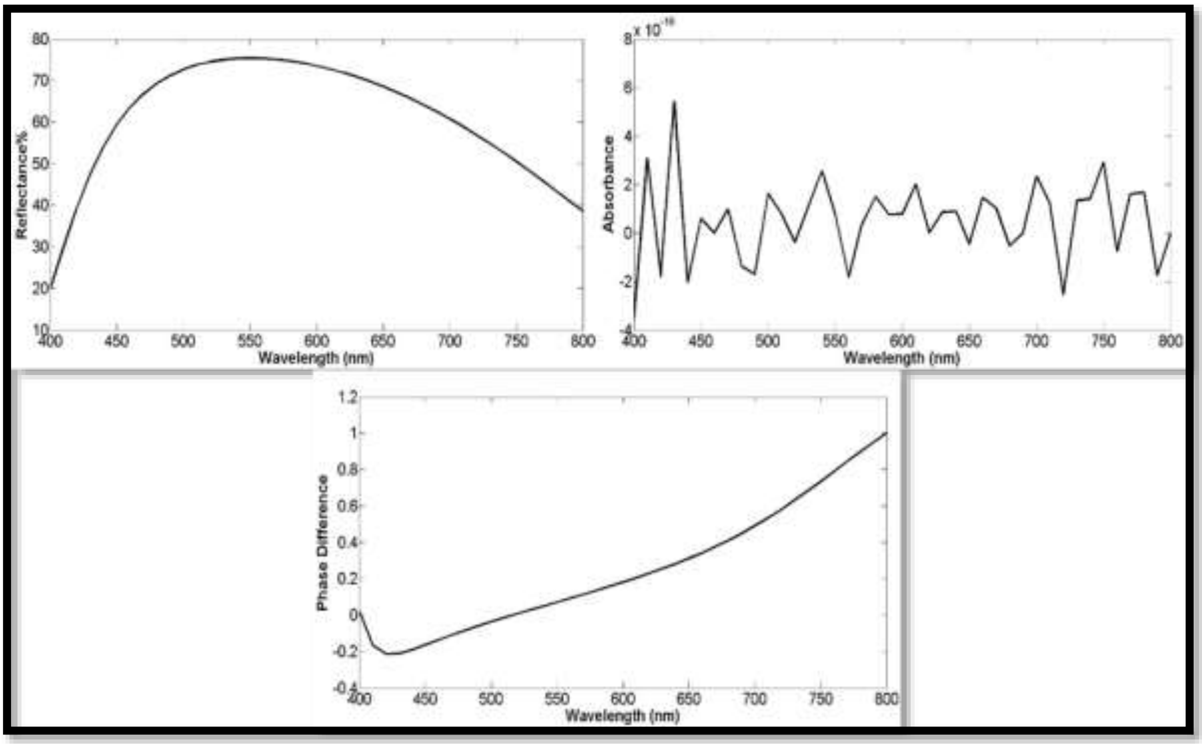

Fig. 6: Reflectance, Absorbance, and Phase Difference for (glass|LH|^2 air) design.

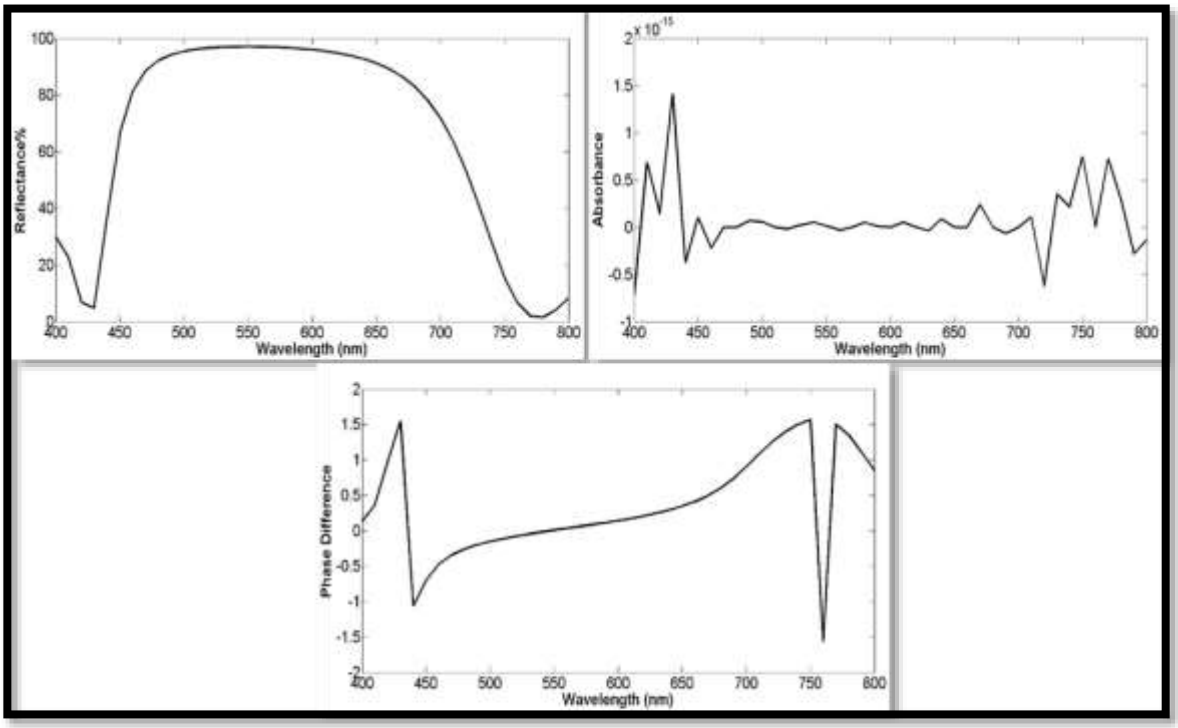

Fig. 7: Reflectance, Absorbance, and Phase Difference for (glass|LH|^4 air) design.

The maximum reflectance can be achieved by using twelve layers depending on the design (glass|LH|^6 air) the reflectance reaches to value (R=99.69%) as shown in figure .8.

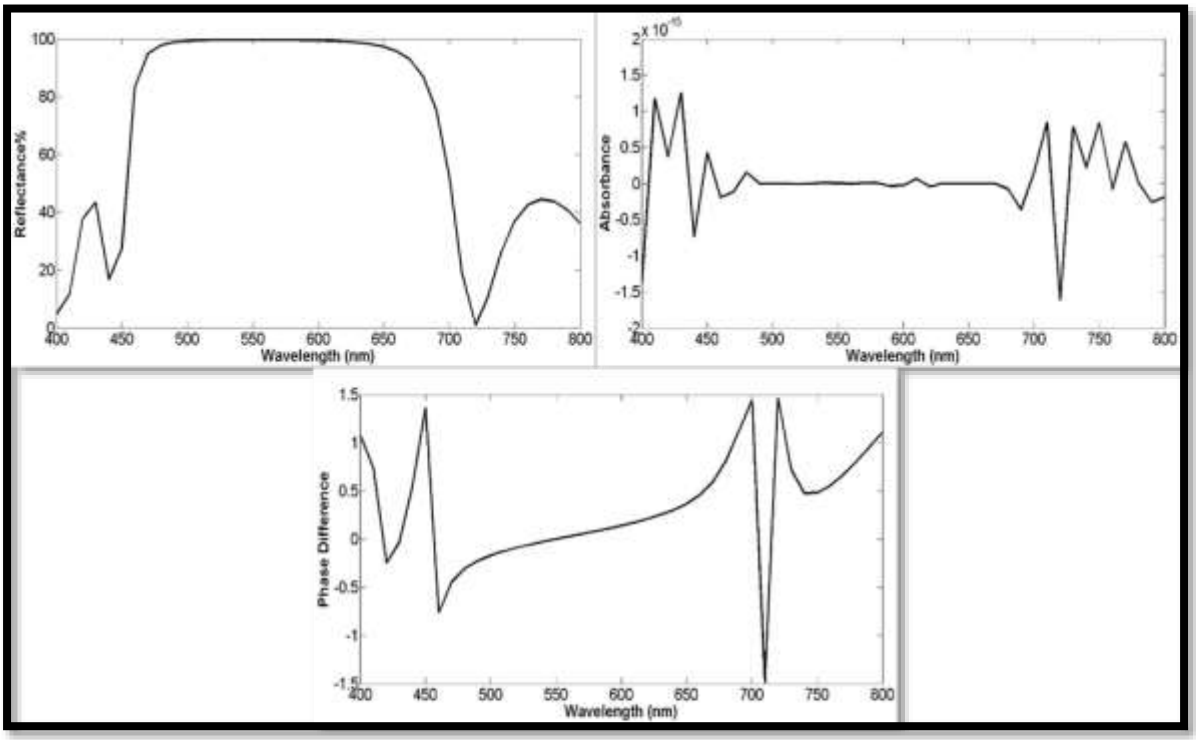

Fig. 8: Reflectance, Absorbance, and Phase Difference for (glass |LH|^6 air) design.

The high reflectance occurred when using the layer of high refractive index as outer layer that explain based on a light wave traveling from a layer of lower refractive index to a layer of higherrefractive index automatically undergoes a phase change of π (180°) upon reflection. A light wave traveling from a layer of higher refractive index to one of lower refractive index undergoes no phase change upon reflection then the reflection occurs with light going from air of a lower refractive index n_0 toward a layer of the higher refractive indexn_H.Light reflected within the layers of high index does not shift its phase, whereas light within the low index shifts by 180°. Taking into account the travel difference in multiples of $2 \times \frac{\lambda}{4}$, the successive reflections recombine constructively at the front surface having the same phase shift, producing a highly reflected beam.Figures shows the phase difference at the design wavelength $\lambda_\circ = 550\, nm$ is zero this illustrates that all rays reflected has the same phase. The phase difference depends upon the films thickness and refractive index, that known as optical path thickness.The reflectivity increases with increases the number of bi- layers, but this increase in the number of layers caused a mechanical stress and damages the coating. To reduce mechanical stressand to increase the stability of the coatingit is necessary to reduce the number of layers by choosing suitable materials that gives greater refractive index ratio $(\frac{n_H}{n_L})$.The refractive index ratio of the two chosen materials that will determine the number of layers needed.The spectral bandwidth of high reflectance increases with the $(\frac{n_H}{n_L})$ ratio (Sharma, 2006). Figures shows that the absorbance is approaching zero at central wavelength (550nm) and shall be low at other wavelengths when using dielectric materials in design.

Conclusions:

Improvement the reflectance of a glass substrate within the visible region (400-800 nm) by adding successive dielectric layers of alternating high refractive index from TiO_2 and low refractive index from MgF_2 material with quarter wave thickness for each layer respectively. The reflectance increases by increasing the number of layers and the high reflectance occurred when using the layer of high refractive index as outer layer. The width of the reflectance does not affected by increasing the number of layers.

ACKNOWLEDGEMENTS

Authors would like to thank Department of Physics, College of Science, Wasit University.

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