Applied Physics Research; Vol. 5, No. 1; 2013
ISSN 1916-9639 E-ISSN 1916-9647
Published by Canadian Center of Science and Education

Designing High Reflectivity Omnidirectional Coating of Mirrors for Near Infrared Spectrum (700-2500 nm)

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Received: August 21, 2012 Accepted: September 10, 2012 Online Published: January 16, 2013

doi:10.5539/apr.v5n1p102 URL: http://dx.doi.org/10.5539/apr.v5n1p102

Abstract

In this paper, a high reflection coating is designed depending on the variable of refractive indices for NIR spectral region (700-2500 nm) by the use of the computer program MATLAB version 7. We could find the reflective 99.62% for seven layers at the incident angels (90°, 40°) in the wavelength (1064 nm) for coatings (Si, MgF_2), substrata BK7 (relatively hard borosilicate crown glass with high homogeneity), which is used for laser application such as the ND:YAG laser (1060 nm), and R=98.37% for coatings (SbSe, Na_3AIF_6) and substrata glass for eleven layers at θ=90° which covers the wavelength from (955.6 nm) to (1622 nm) and represents the complete range for optical telecommunication band (short (S) 1460-1530 nm, conventional (C) 1530-1560 nm and long (l)1560-1620 nm). The results show that the reflectivity of the stack increases with the number of layers in the stack, the best layer number is nine which has a reflective of 99.62% at (1060 nm), as shown in Figure 4a. Also the reflective changes with incident angel; the best angel is (40°) which gives the convergent reflective for electric and magnetic polarization 99.91% and 99.36%, respectively for the wavelength (1060 nm).

Keywords: designing, coating, reflectivity, near infrared

1. Introduction

Infrared waves are electromagnetic waves with frequencies lower than visible light. The lowest frequencies of visible light are red, so one call the lower frequencies infrared, meaning beyond red. This type of electromagnetic radiation is widely used for local communications (Daniel et al., 1996). The IR spectral region of the electromagnetic spectrum extends from the red end of the visible spectrum to the microwave region; it includes radiation with wave numbers ranging from about 14,000 to 20 cm^{-1}, or wavelengths from 700 to 50000 nm. The near-IR (NIR) region extends from the visible region at (700 nm) to the mid-IR region at (2500 nm) (Michele et al., 1995).

When the electromagnetic wave is incident on plane surface bonding two substances of indices n and $\bar{n}$, this wave suffer absorption, reflection, dispersion and transmittance , according to Equation (1), as shown in Figure 1 (Stenzel, 2005):

$$T+R+A+S=1 \tag{1}$$

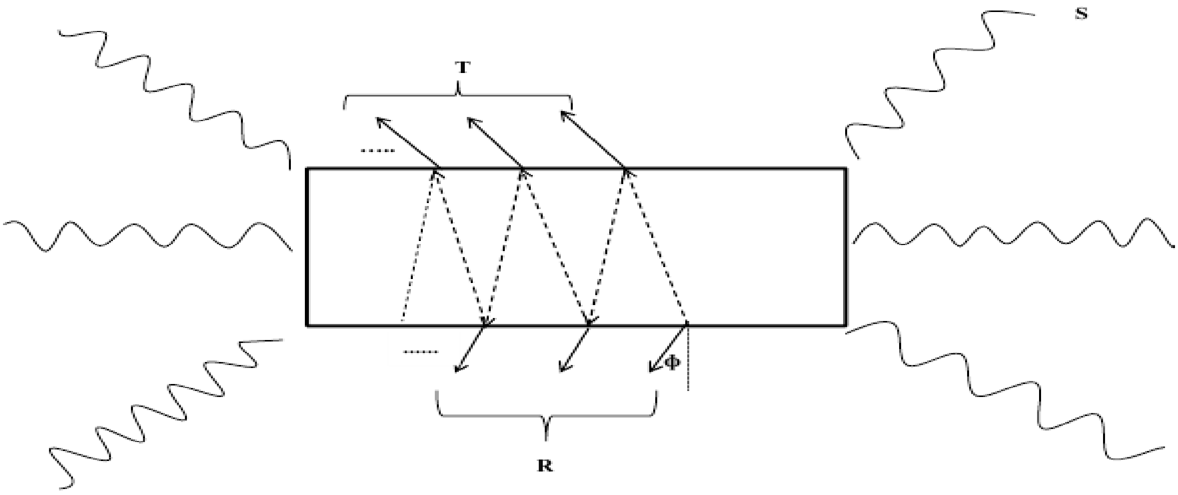


Figure 1. The definitions of T, R, and S. ϕ are the incidence angle (Stenzel, 2005)

Where transmittance is T, the specula reflectance R, the optical scatter S, the absorptions A, as conservation of energy. But as we work with homogenous materials and flat surfaces, scatter does not occur and Equation (1) becomes (Stenzel, 2005):

$$T+R+A=1 \tag{2}$$

Multilayer optical thin film coating has extensively been used for reflectivity modulation in various optical and optoelectronic components (Kheraj et al., 2008). It's has a wide range of applications, such as displays; applications of near-infrared, such as camera lenses, mirrors, and filters; eyeglasses; mirrors, laser windows, and polarizes; optics of photocopiers and compact disks; optical communications; home appliances, such as heat reflecting oven windows ((Kheraj et al., 2008; Sophocles, 2010)

Multilayer optical thin film coating include anti reflection (AR) and high reflection (HR) coating on leaser diode facets (Kheraj et al., 2008). Laser and fabry-perot resonators require high reflectivity that is unattainable from metallic films which also suffer from high absorption in a lesser degree (Sharma, 2006). AR coating is used on lenses of camera and telescope and fabrication of polarizing beam splitters and various optical filters (Kheraj et al., 2008).

The main interest in dielectric mirrors is that they have extremely low losses at optical and infrared frequencies, as compared to ordinary metallic mirrors. On the other hand, metallic mirrors reflect over a wider bandwidth than dielectric ones and from all incident angles. A dielectric mirror consists of identical alternating layers of high and low refractive indices, as shown in Figure 2(a). The optical thicknesses are typically chosen to be quarter-wavelength long, $n_H l_H = n_L l_L = \frac{\lambda_\circ}{4}$ at some operating wavelength λ_0 (center wavelength). The standard arrangement is to have an odd number of layers, with the high index layer being the first and last layer (Sophocles, 2010).

The Fresnel amplitude reflection coefficient (r) for an interface between two Non-absorbing media at normal incidence can be represented by the following equation (Ronald, 2002):

$$r = \frac{n_1 - n_2}{n_1 + n_2} \tag{3}$$

where n_1 and n_2 are the (real) indices of refraction of the two media. For the more general case of absorbing media with complex refractive indices $nj = nj - ikj (j = 1,2, \ldots .)$ the reflection intensity coefficient (R) is the amplitude reflection coefficient (r) times its complex conjugate (r*) (Wwillely, 2002):

$$R=rr^* \tag{4}$$

Lusk and Placido (2005), used thin-film SiO_2 and Si as coating and glass as the substrate and got the reflectivity R = 99.5 % at a design wavelength 1540 nm for 14 layers. AL-Dujely Wasfi Hammed Rasheed (2000) used thin-film ZnS, MgF_2 as coating and BK7 as the substrate and he got the reflectivity R=82.5 % at a design wavelength 1060 nm for five layers. Kherj, Panchal, Desai and Potbhare (2008) used thin-film AL_2O_3 and Si as coating and GaAs as the substrate and got the reflectivity R=98.66 % at a design wavelength 890nm for four layers. Kohoutek et al. (2009) used thin-film GeS and SbSe as coating and SiO_2 as the substrate and got the reflectivity R=98.8 % at a design wavelength 1550 nm for 15 layers.

In our work, we will design a computer program to calculate and optimize the reflectivity as a function of wave length for near IR spectrum (700-2500 nm), for different dielectric materials and we will see the effect of substrate, number of layers and incident angle of NIR rays on reflectivity of these materials.

2. Theoretical Basis

The multilayer optical coating usually consists of a stack of several layers of non-absorbing dielectric materials with different refractive indices (Kheraj et al., 2008). The all-dielectric multilayer coating can achieve high reflectivity with minimal scattering and absorption losses (Sharma, 2006)

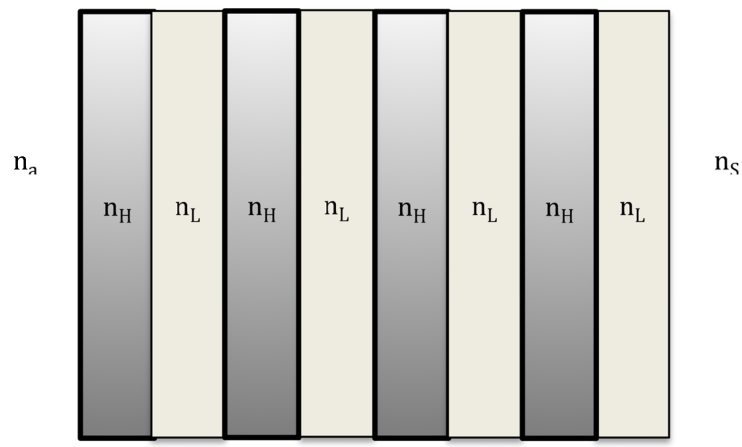


Figure. 2a. Stack of alternate high and low refractive index quarter-wave layers for high reflectance applications (Sharma, 2006)

Suppose that a plane electromagnetic wave with wave-vector K and electric field amplitude E_0 is incident on a plane surface separating isotropic media with refractive indices n_1 and n_2. The angle of incidence between the incident wave-vector k and the normal to the surface n̂ isîor θ. Without loss of generality, one can separately treat the two cases where the incident vector E lies in the plane defined by k and n̂, denoted by ││. Other names which are commonly used for ││ are P or TM (transverse magnetic), and that where E is normal to this plane, denoted by ⊥ (other names S or TE (transverse electric) (Lipson et al., 2010).

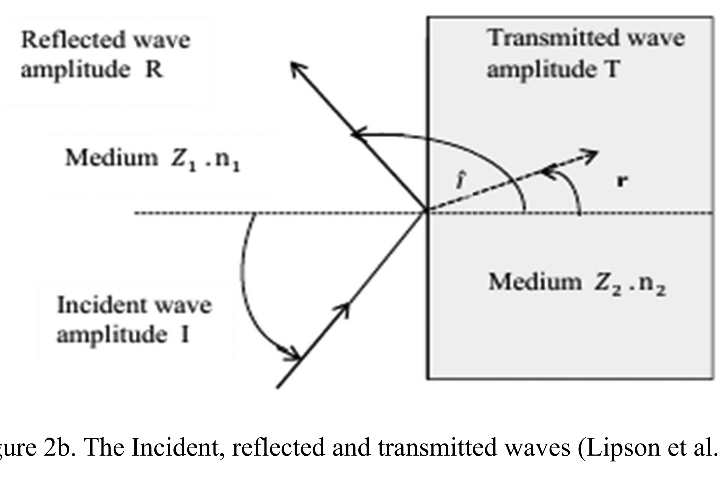


Figure 2b. The Incident, reflected and transmitted waves (Lipson et al., 2010)

Figure 2b shows the geometry of this situation. Notice that reflected and transmitted waves have been introduced. The plane containing the incident wave-vector k, the reflected and transmitted wave-vector and the normal $\hat{n}$ is the (x, z) plane, and the vector $\hat{n}$ is along the z- direction. We denote the amplitudes (electric field magnitudes) of the incident, reflected and transmitted waves by I, R and T respectively. The magnitudes of the wave-vectors in the two media are K_1 and K_2 and clearly $k_1/n_1 = k_2/n_2 = k_0$ since both waves have the same frequency. At normal incidence, the reflection and transmission coefficients for the two polarizations are equal and are given by (Lipson et al., 2010):

$$R = \frac{n_1 - n_2}{n_1 + n_2} = \frac{1 - n_r}{1 + n_r} \quad (5)$$

$$T = \frac{2n_1}{n_1 + n_2} = \frac{2}{1 + n_r} \quad (6)$$

where n_r is the relative refractive index between the two media. We define reflection and transmission coefficients for polarization TE or ⊥ (denoted by the subscript ⊥) (A. LIPSON et al., 2010):

$$R_\perp = \frac{n_1 \cos\hat{\imath} - n_2 \cos\hat{r}}{n_1 \cos\hat{\imath} + n_2 \cos\hat{r}} = \frac{\cos\hat{\imath} - n_r \cos\hat{r}}{\cos\hat{\imath} + n_r \cos\hat{r}} \quad (7)$$

$$T_\perp = \frac{2n_1 \cos\hat{\imath}}{n_1 \cos\hat{\imath} + n_2 \cos\hat{r}} = \frac{2\cos\hat{\imath}}{\cos\hat{\imath} + n_r \cos\hat{r}} \quad (8)$$

The coefficients for the | | plane of polarization can be worked out similarly (Lipson et al., 2010):

$$R_{||} = \frac{n_1 \cos\hat{r} - n_2 \cos\hat{\imath}}{n_1 \cos\hat{r} + n_2 \cos\hat{\imath}} = \frac{\cos\hat{r} - n_r \cos\hat{\imath}}{\cos\hat{r} + n_r \cos\hat{\imath}} \quad (9)$$

$$T_\perp = \frac{2n_1 \cos\hat{r}}{n_1 \cos\hat{r} + n_2 \cos\hat{\imath}} = \frac{2\cos\hat{r}}{\cos\hat{r} + n_r \cos\hat{\imath}} \quad (10)$$

These functions are known as Fresnel coefficients (Lipson et al., 2010).

A high reflectance coating can be designed by using dielectric quarter-wave stack of alternate high- and low-refractive index materials. If n_H and n_L are the indices of the high- and low-index layers and if the stack is arranged, the high-index layers are outermost at both sides. The transformation matrix for a stack of N pairs of quarter-wave layers of high and low refractive index materials can be expressed in the form (Sharma, 2006):

$$M = (M_H M_L)^N \quad (11)$$

where

$$M_H = \begin{vmatrix} \cos\beta_H t_H & \left(-\frac{i}{y_H}\right) \sin\beta_H t_H \\ -iy_H \sin\beta_H t_H & \cos\beta_H t_H \end{vmatrix} \quad (12)$$

$$M_L = \begin{vmatrix} \cos\beta_L t_L & \left(-\frac{i}{y_L}\right) \sin\beta_L t_L \\ -iy_L \sin\beta_L t_L & \cos\beta_L t_L \end{vmatrix} \quad (13)$$

therefore,

$$M = \left[\begin{pmatrix} 0 & \frac{-i}{y_H} \\ -iy_H & 0 \end{pmatrix}\begin{pmatrix} 0 & \frac{-i}{y_L} \\ -iy_L & 0 \end{pmatrix}\right]^N \quad (14)$$

$$M = \begin{bmatrix} \left(\frac{-y_L}{y_H}\right)^N & 0 \\ 0 & \left(\frac{-y_H}{y_L}\right)^N \end{bmatrix} \quad (15)$$

where the normal incidence was assumed to be :

$$\beta_H t_H = \frac{2\pi}{\lambda_v} n_H t_H = \pi/2 \quad for\ \lambda_v = \lambda_o$$

$$\beta_L t_L = \frac{2\pi}{\lambda_v} n_L t_L = \pi/2 \quad for\ \lambda_v = \lambda_o$$

where (t) is the thickness, $\beta_H = n_H\left(\frac{2\pi}{\lambda}\right)\cos\varphi_H$ and $\beta_L = n_L\left(\frac{2\pi}{\lambda}\right)\cos\varphi_L$ in the process of wave propagation through an N layer stack. n_H, n_L are indices of the high and low index layers, where θ, φ are the angle of reflection and angle of refraction, $y_{0=}{}^{n_0}/_{cos\theta}$, $y_{1=}{}^{n_1}/_{cos\phi_1}$, and $y_{s=}{}^{n_s}/_{cos\psi}$ as shown in Figure 3 (Sharma,2006).

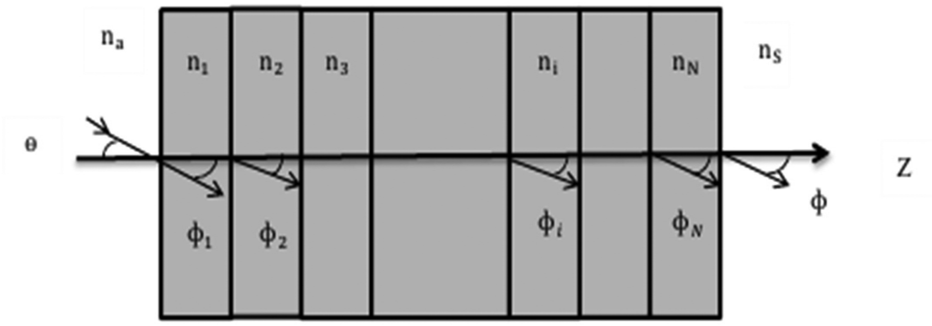


Figure 3. The N layer stack; φ_j and n_j are the angles of refraction and index of refraction of the jth layer (Sharma, 2006)

The coefficients y_L, y_H can be calculated for either state of polarization from the knowledge of indices of refraction of the films and angles of refraction in each film. The latter can be obtained from:

$$n_0 sin\theta = n_1 sin\phi_1 = n_2 \sin\phi_{2= \dots =} n_N \sin\phi_N = n_s \sin\phi_N = n_s \sin\psi\ .$$

giving the reflectance of the stack as (Sharma, 2006):

$$R = r^2 = \left|\frac{n_s\left(\frac{n_H}{n_L}\right)^{2N} - n_o}{n_s\left(\frac{n_H}{n_H}\right)^{2N} - n_o}\right|^2 \tag{16}$$

the reflectance in air or free space is then (Al-Dujely, 2000; Macleod, 1986, 2001):

$$R = \left|\frac{1-\left(\frac{n_H}{n_L}\right)^{2N}\left(\frac{n_H{}^2}{n_S}\right)}{1+\left(\frac{n_H}{n_L}\right)^{2N}\left(\frac{n_H{}^2}{n_S}\right)}\right|^2 \tag{17}$$

The reflectivity of the stack increases with the number of layers in the stack and the spectral bandwidth of high reflectance increases with the ${}^{n_H}/_{n_L}$ ratio. Multi-layer broad band high reflectance dielectric mirrors are now readily available (Sharma, 2006). The reflectance of such a film depends on the constructive or destructive interference of light reflected at successive boundaries of different layers of the multilayer stack (Kheraj et al., 2008).

High reflectance coating usually consists of alternate quarter-wave layer of materials with high and low indices of refraction ($n_H l_H = n_L l_L = \frac{\lambda_o}{4}$) (Wwillely, 2002). The standard arrangement is to have an odd number of layers, with the high index layer being the first and last layer (Orfanidis, 2010).

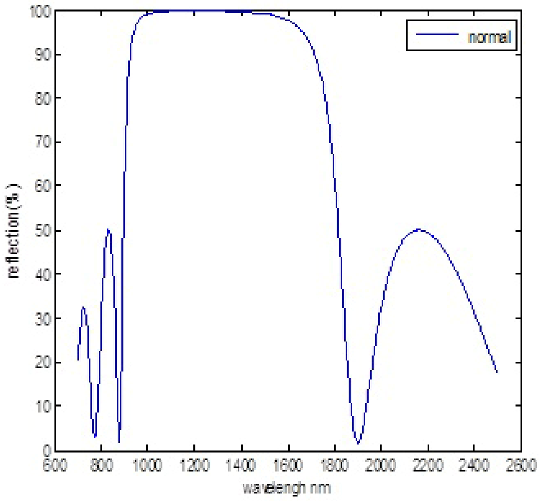
3. Results and Discussion

We design a computer program using MATLAB version 7 to calculate and optimize the high-reflectivity for different materials (coatings) within near infrared wave. This program depends on refractive index of materials (coating), number of layers and incident angle.

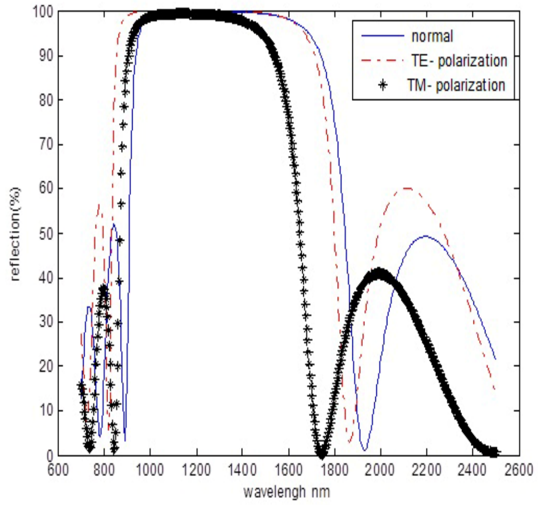
Figures (4) and (5) show that the coating consists of (Si) as high refraction index (3.42) (Farlow & Boatener, 1997), (MgF_2) as low refraction index (1.37) (Al-Dujely, 2000) and the substrate (BK7) with the refractive index (1.505) (BK7 used because it has low losses and high stability, Al-Dujely, 2000), for the central wavelength

(λ_0=1200 nm). The results are shown in Table 1.

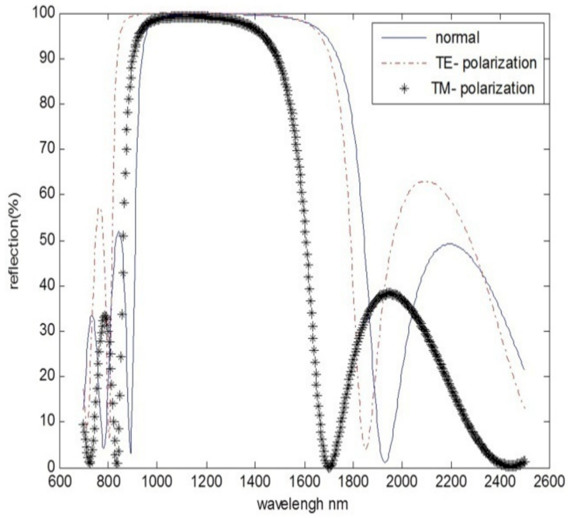
Figures 6 and 7 show that the coating consists of (SbSe) as high refraction index (3.23 (Kohoutek et al., 2009)), (Na_3AlF_6) as low refraction index (1.35 (Kim & Hwangbo, 2002)) and the substrate (glass) with the refractive index (1.52 (Lusk & Placido, 2005)), for the central wavelength (λ_0=1200 µm).The results are shown in Table 2:



(a)

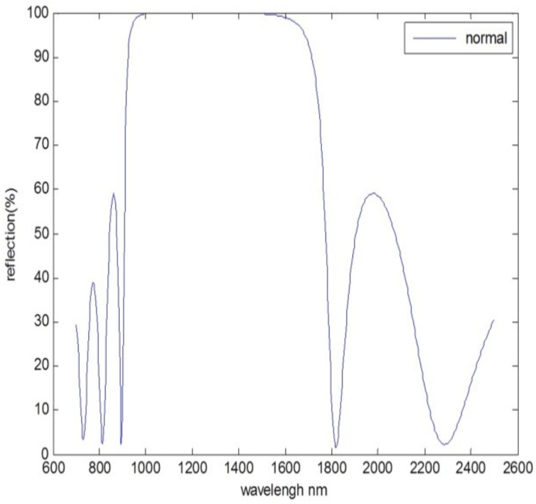


(b)

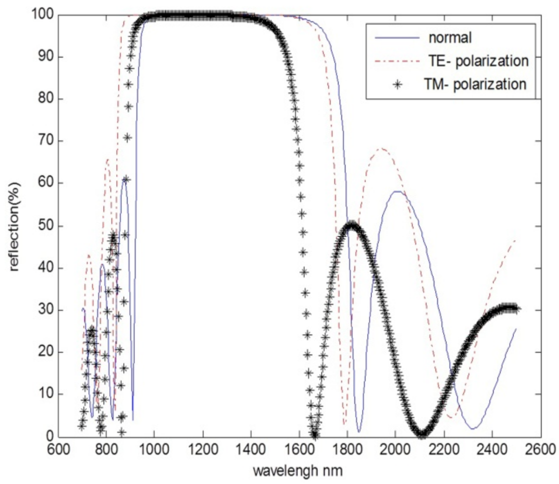


(c)

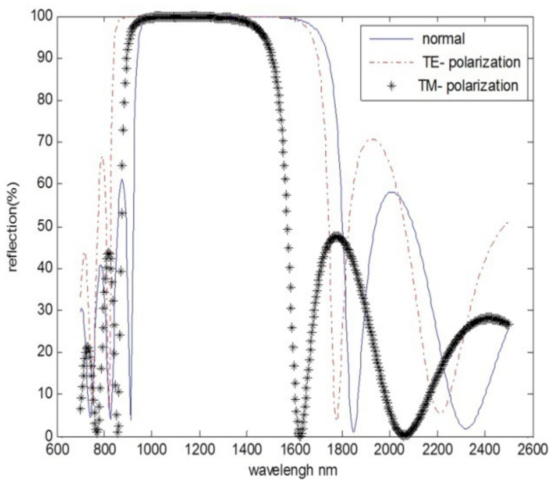
Figure 4. The Reflectivity as function of wavelength for coating n(Si)=3.42, n(MgF_2)=1.37 and n(BK7)=1.505, for seven layers at incident angle(θ) of [a] 90˚, [b] 40˚ and [c] 45˚



(a)

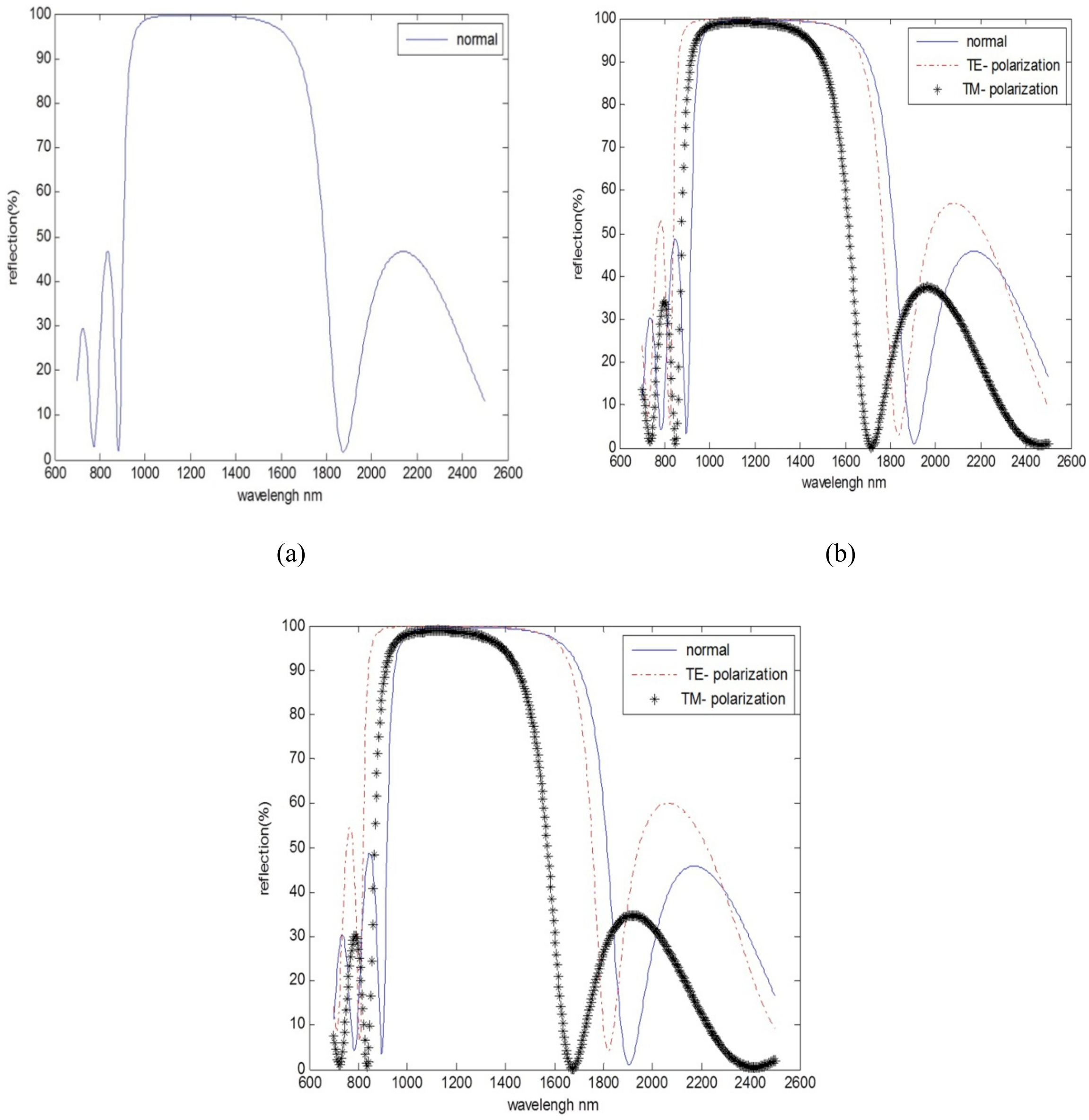


(b)



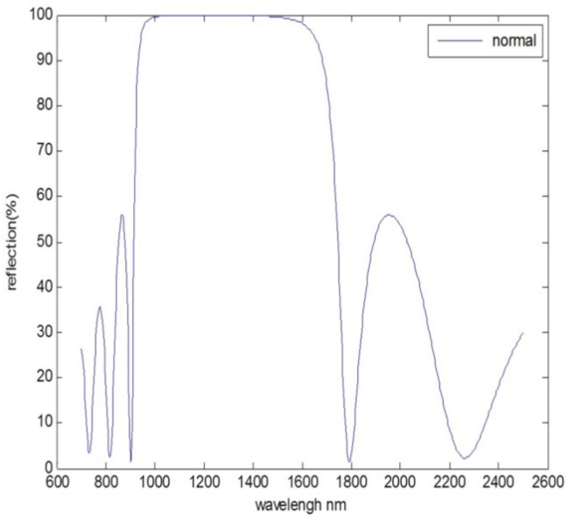
(c)

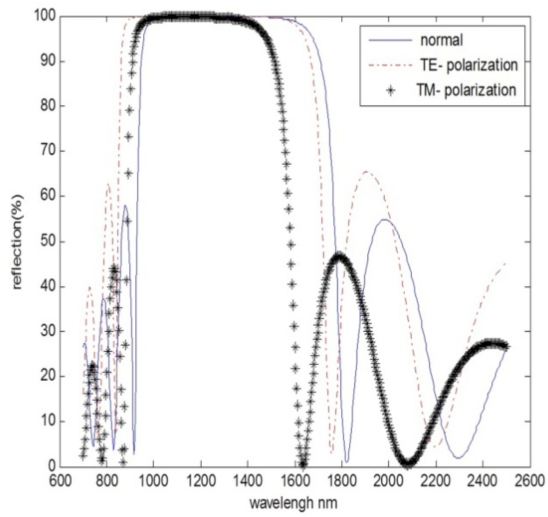
Figure 5. The Reflectivity as function of wavelength for coating n(Si)=3.42 , n(MgF2)=1.37 and n(BK7)=1.505, for nine layers at incident angle(θ) of [a] 90˚, [b] 40˚and [c] 45˚



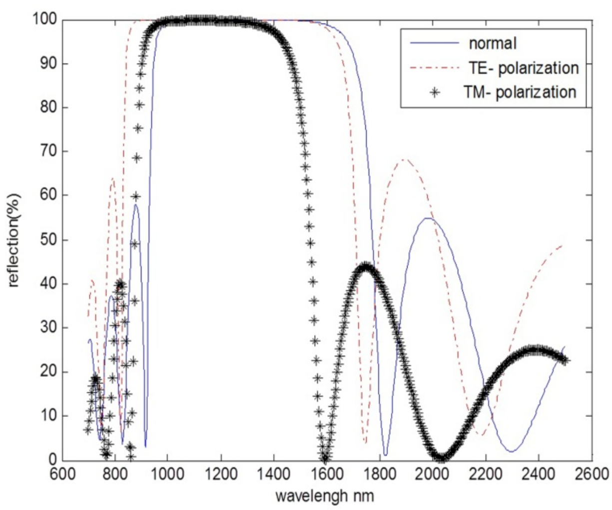
(c)

Figure 6. The Reflectivity as function of wavelength for coating n(SbSe)=3.23, n(Na_3AlF_6)=1.35, n(glass)=1.52, for seven layers at incident angle(θ) of [a] 90˚, [b] 40˚ and [c] 45˚



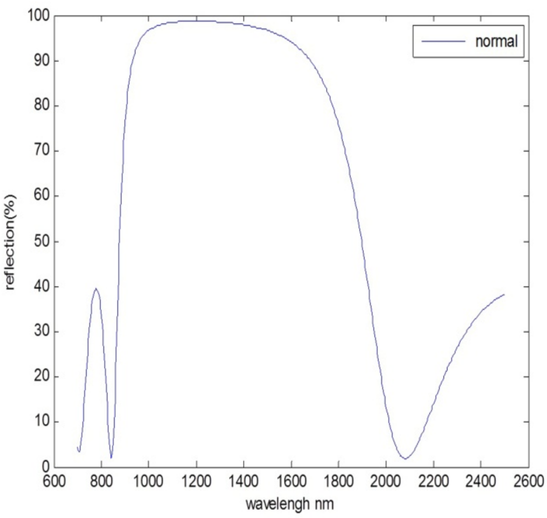


(a) (b)

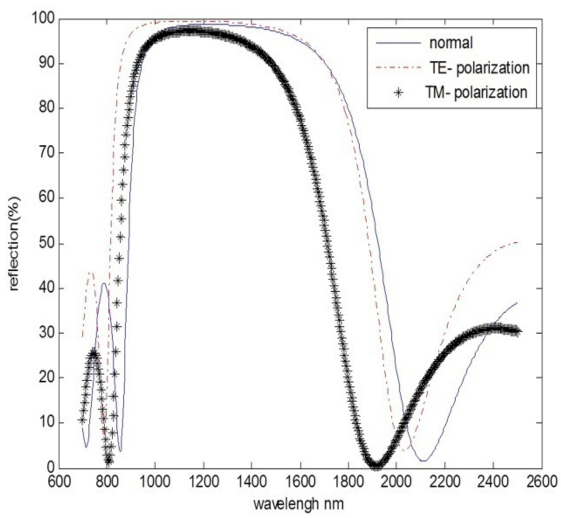


(c)

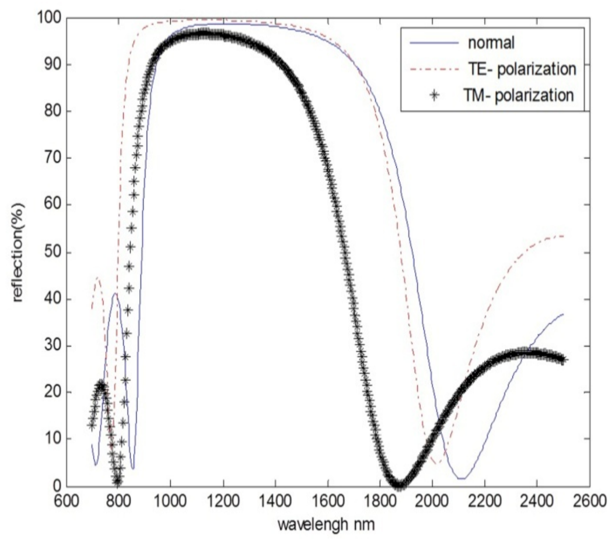
Figure 7. The Reflectivity as function of wavelength for n(SbSe)=3.23, n(Na_3AlF_6)=1.35, n(glass)=1.52, for nine layers at incident angle(θ) of [a] 90˚, [b] 40˚ and [c] 45˚



(a)



(b)



(c)

Figure 8. The Reflectivity as function of wavelength for coating n(Si)=3.42, n(MgF_2)=1.37 and n(BK7)=1.505, for five layers at incident angle(θ) of [a] 90˚, [b] 40˚ and [c] 45˚

The reflectivity of (BK7) is 4.064 %, and when coating one layer from the Si, the reflective becomes R=59.6 %, and if one uses three layers [Si MgF_2 Si], the reflective becomes R=92.07 % at incident angle θ=90˚ at ($\lambda_o = 1200$ nm). This shows that the reflectivity of the stack increases with the number of layers in the stack, according to equation (16).The spectral bandwidth of high reflectance increases with the n_H/n_L ratio (Sharma, 2002). When incident angle θ=90, this reflects that both polarization TE and TM are corresponding.

To obtain a high reflectivity by reducing the number of layers, one can use incident angle as a variable (Kim & Hwangbo, 2002), as the incident angle increases, the admittance of TE polarization increases and that of TM polarization decreases. So the reflection bandwidth of TE polarization is wider than that at normal incidence, and that of TM polarization is narrower. Therefore, at a high incident angle and reference wavelength, the reflectance of TM-polarized light may be quite low in contrast to the high reflectance of TE-polarized light (Kim & Hwangbo, 2002). It appears that the best coating is when R=99.79 %at incident angle θ=90˚ and R=99.90 % R=99.31 % for TE, TM respectively at incident angle θ=40˚ for seven layers for coating (MgF_2, Si and substrate

BK7), and R=99.21 %, R=99.13 for TE, TM respectively at incident angle θ=40˚ for nine layers for coating (SbSe, Na_3AlF_6 and substrate glass) to obtain the higher reflectivity and lowest number of layers.

As the incident angel increases the center wavelengths of both reflection bands shift to shorter wavelength region as show in Figures 6(b, c) and 7(b, c) in Table (2).This coating which used BK7 as substrate is used in laser applications as coating for the ND:YAG laser (1060 nm) (Al-Dujely, 2000). In this paper, the reflectivity for the coating was R=98.07 % at incident angle θ =90˚, R=99.31 for TE and R=96.92 % for TM, θ=45˚, R=99.45 % for TE and R=96.35 % for TM for N=2, as shows in Figure (8a, b, c) when N=3, R=99.61 % at incident angle θ =90˚, R=99.91 for TE and R=99.35 % for TM for θ=40˚ and when θ=45˚ R=99.93% for TE and R=99.2% for TM, as shows in Figure 4 (a ,b, c). It appears that the best coating was R=99.91% ,R=99.35% at θ=90˚, θ=40˚, respectively for N=3, the best coating was when obtaining the higher reflectivity and lower number of layers, and the best incident angle was θ=40˚ because the beam attenuation increases with increasing the angle of incidence beyond the critical angle(Sophocles, 2010).

When comparing these results with the results of AL-Dujely Wasfi Hammed Rasheed (2000), who used thin-film ZnS, MgF_2 as coating and BK7 as the substrate and got the reflectivity R =82.5 % at a center wavelength of 1060 nm in five layers, it seems that the coating one can design when N=3 is the best.

The substrate (glass) which has the reflectivity R=4.258 % with the coating (SbSe) and (Na_3AlF_6) has a reflectivity greater than 98.37 % for the range (955.6-1622nm) for N=5 at θ=90˚ as shows Figure 7(a). This coating is used in laser applications and optical communications. So that it covers bands S, C and L for optical telecommunication where (C band is 1530-1560 nm), (S band is 1460-1530 nm) and (L band is 1560-1620 nm) (Kim & Hwangbo, 2002). The coating one can design when N=5 is best compared with that of Kim and Hwangbo used glass as the substrate and (TiO_2, SiO_2) as coating and obtained a reflectivity greater than 98 % at TM , θ=85˚, θ=0˚ for (N=30) covering the S, C and L from 1286.8 nm to 1629.1 nm (Kim & Hwangbo, 2002).

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To obtain a high reflectivity by reducing the number of layers, one can use incident angle as a variable (Kim & Hwangbo, 2002), as the incident angle increases, the admittance of TE polarization increases and that of TM polarization decreases. So the reflection bandwidth of TE polarization is wider than that at normal incidence, and that of TM polarization is narrower. Therefore, at a high incident angle and reference wavelength, the reflectance of TM-polarized light may be quite low in contrast to the high reflectance of TE-polarized light (Kim & Hwangbo, 2002). It appears that the best coating is when R=99.79% at incident angle θ=90˚ and R=99.90 % R=99.31% for TE, TM respectively at incident angle θ=40˚ for seven layers for coating (MgF_2, Si and substrate BK7), and R=99.21 %, R=99.13 for TE, TM respectively at incident angle θ=40˚ for nine layers for coating (SbSe, Na_3AlF_6 and substrate glass) to obtain the higher reflectivity and lowest number of layers.

As the incident angel increases the center wavelengths of both reflection bands shift to shorter wavelength region as show in Figures 6 (b, c) and 7 (b, c) in Table 2. This coating which used BK7 as substrate is used in laser applications as coating for the ND:YAG laser (1060nm) (Al-Dujely, 2000). In this paper, the reflectivity for the coating was R=98.07 % at incident angle θ=90˚, R=99.31 for TE and R=96.92 % for TM, θ=45˚, R=99.45 % for TE and R=96.35 % for TM for N=2, as shows in Figure 8 (a, b, c) when N=3, R=99.61 % at incident angle θ =90˚, R=99.91 for TE and R=99.35 % for TM for θ=40˚ and when θ=45˚ R=99.93 % for TE and R=99.2 % for TM, as shows in Figure 4 (a, b, c). It appears that the best coating was R=99.91 %, R=99.35 % at θ=90˚, θ=40˚, respectively for N=3, the best coating was when obtaining the higher reflectivity and lower number of layers, and the best incident angle was θ=40˚ because the beam attenuation increases with increasing the angle of incidence beyond the critical angle (Sophocles, 2010).

When comparing these results with the results of AL-Dujely Wasfi Hammed Rasheed", 2000, who used thin-film ZnS, MgF_2 as coating and BK7 as the substrate and got the reflectivity R=82.5 % at a center wavelength of 1060 nm in five layers, it seems that the coating one can design when N=3 is the best.

The substrate (glass) which has the reflectivity R=4.258 % with the coating (SbSe) and (Na_3AlF_6) has a reflectivity greater than 98.37 % for the range (955.6-1622nm) for N=5 at θ=90˚ as shows Figure 7a. This coating is used in laser applications and optical communications. So that it covers bands S, C and L for optical telecommunication where (C band is 1530-1560 nm), (S band is 1460-1530 nm) and (L band is 1560-1620 nm) (Kim & Hwangbo, 2002). The coating one can design when N=5 is best compared with that of Kim and

Hwangbo used glass as the substrate and (TiO_2, SiO_2) as coating and obtained a reflectivity greater than 98% at TM, θ=85˚, θ=0˚ for (N=30) covering the S,C and L from 1286.8 nm to 1629.1 nm (Kim & Hwangbo, 2002).

Table 1. The values of Reflectivity coating Si, MgF_2 of the substrate (BK7) for incident angles (90°, 40°, 45°)

Number of Figure/ and Number of layers	Incidence angle	Wavelength nm	Reflectivity R
4.a / N=3	90°	1056-1384	R > 99.6%
4.b / N=3	40°	944.8-1391	R_{TE}>99.7
		1010-1269	R_{TM}>99.04
4.c / N=3	45°	923.2-1391	R_{TE}>99.72
		980.8-1269	R_{TM}>98.57
5.a / N=4	90°	1053-1391	R>99.91
5.b / N=4	40°	941.2-1391	R_{TE}>99.94
		941.2-1391	R_{TM}>99.07
5.c / N=4	45°	916-1391	R_{TE}>99.94
		916-1287	R_{TM}>98.11

Table 2. The values of Reflectivity coating SbSe, Na_3AlF_6 of the substrate (glass) for incident angles (90°, 40°, 45°)

Number of Figure / and Number of layers	Incidence angle	Wavelength nm	Reflectivity R
6.a / N=4	90°	955.6-1622	R>97.25
6.b / N=4	40°	869.2-1578	R_{TE}>98.02
		930.4-1406	R_{TM}>97.98
6.c / N=4	45°	858.4-1539	R_{TE}>99.04
		905.2-1406	R_{TM}>95.5
7.a / N=5	90°	955.6-1622	R>98.37
7.b / N=5	40°	880-1564	R_{TE}>99.59
		930.4-1406	R_{TM}>99.06
7.c / N=5	45°	858.4-1535	R_{TE}>99.58
		901.6-1409	R_{TM}>96.94

4. Conclusion

From the above result, one can conclude that the reflectivity for coating within near infrared waves (700-2500 nm) depending on the coating type, number of layers and angle of incidence. The addition of layers does not affect the width of zone of high reflectance, but increases the reflectivity within. The best coating used in laser applications as coating for the ND:YAG laser (1060nm) is (Si ,MgF_2) on the substrata BK7 which gives the best reflection R=99.61 % at θ=90˚, R=99.91 for TE and R=99.35 % for TM for θ=40˚ at N=3. The best coating used in optical communications is (SbSe, Na_3AlF_6) on the substrata which gives the best reflection (greater than 98.37 %) for the range(955.6-1622 nm) at θ=90˚ for N=5.

References

Al-Dujely. (2000). *Mirrors coating for the ND:YAG laser (1.06μm)*. Iraq, Military College of Engineering.

Farlow, G. C., & Boatener, L. A. (1997). Irradiation effects in MgF2 coating on Si and GaAs substrates. *Optical Materials, 8*(4), 279-286. http://dx.doi.org/10.1016/S0925-3467(97)00051-7

Finkenthal, D., Greco, B., Halsey, R., Halsey, R., Pena, L., Rodecker, S., … Schissel, D. P. (1996). Introduction to the Electromagnetic Spectrum. The Fusion Education, *General Atomics*.

Keseibrener, M., & Ruschin, S. (1999). Interferometric variable reflectivity mirror: experimental results. *Optical Materials, 13*(1), 97-100. http://dx.doi.org/ 10.1016/S0925-3467(99)00017-8

Kheraj, V. A., Panchal, C. J., Desai, M. S., & Potbhare, V. (2008). *Simulation of reflectivity spectrum for non-absorbing multilayer optical thin films*. Springer-Verlag. http://dx.doi.org/10.1007/s12043-009-0081-0.

Kohoutek, T., Orave, J., Prikryl, J., Mistrik, J., Wagner, T., & Frumar, M. (2009). Near infrared quazi-omnidirectional reflector in chalcogenide glasses. *Optical Materials, 32*, 154-158. http://dx.doi.org/10.1016/j.optmat.2009.07.004.

Li, S. Z., Chu, R. F., Liao, S. C. & Zhang. L. (2007). Illumination Invariant Face Recognition Using Near-Infrared Images. *IEEE T. PAMI, 29*(4), 627-639. http://dx.doi.org/10.1109/TPAMI.2007.1014

Lipson, A., Lipson, S. G., Lipson, H., & FRS. (2010). *Optical Physics* (4th ed.). New York, NY: Cambridge University Press.

Lusk, D., & Placido, F. (2005). Omnidirectional mirror coating design for infrared applications. *Thin Solid Films*, *492*, 226-231. http://dx.doi.org/10.1016/j.tsf.2005.06.053

Macleod, H. A. (1986, 2001). *Thin-Film Optical Filters* (3rd ed.). Physics Publishing, University of Arizona

Michele, R., Derrick, D., & James, M. L. (1995). *Infrared spectroscopy in conservation science*. Los Angeles: Getty Conservation Institute.

Sharma, K. K. (2006). *OPTICS Principles and Applications*. Los Angeles: Elsevier Inc. The Getty Conservation Institute.

Sophocles, J. O. (1999-2010). *Electromagnetic Waves and Antennas*. Rutgers University

Stenzel, O. (2005). *The Physics of Thin Film Optical Spectra*. Berlin, Heidelberg: Springer. http://dx.doi.org/10.1007/3-540-27905-9

Kim, S. H., & Hwangbo, C. K. (2002). Design of omnidirectional high reflectors with quarter–wave dielectric stacks for optical telecommunication bands. *Applied Optics, 41*, 3187-3192. http://dx.doi.org/10.1364/AO.41.003187

Wwillely, R. R. (2002). *Practical Design and Production of Optical Thin Films*. New York, Basel: Marcel Dekker, Inc.