Design High performance multilayers cold mirror

Ansam Qassim Gadhban¹, Harakat Mohsin Roomy², Sarah K Taha³

¹Department of Physics, Madenet Al-Elem University College, 
²Ministry of education, Baghdad, Iraq
³Department of Physics, College of Science for Women, Baghdad University, Iraq

E-mail: Ansam.qasim@mauc.edu.iq

Abstract. The optical design process includes a myriad of tasks that the designer must be performed and consider in the process of optimizing the performance of the optical system. In this article, a design based on four groups of materials for a multilayer dielectric cold mirror: V₂O₅\MgF₂, SiC\MgF₂, TiO₂\MgF₂, and Al As\MgF₂ where MgF₂ represents low refractive index and other material in each group represent high refractive index. A cold mirrors are a special dielectric mirrors that reflects the entire visible wavelength band, while the transmitting infrared wavelength band. These systems of mirrors are constructed for an event angle from 0 ° to 45 ° and are modeled with interference filters-like multi thin layer dielectric coatings. The results of our work designed shows the mirror based on Al As/MgF₂ is the most promising design for cold mirror with the highest reflection in the visible region and the highest Transition in the IR region. In the spectrum range of 400-800 nanometers, the average transmission is much less than 1 %, while the average transmission is 95 percent in the wave band 800-2500 nanometer.

Key words: Multilayers Coatings, Cold mirror, Characteristic matrix.

1. Introduction

In optical manufactured devices, optical coatings are founded to be an important requirement. Through changing the direction of propagation, spectrum, the magnitude, phase or polarization, can be used to match the optical media and regulating the light radiation [1]. These optical coatings consisting of one or more of thin layers of metal or insulating materials, [2,3] has a number of important applications in many branches of science and technology [4]. Thin coatings have been used to improve a glass's color and efficiency of energy and as reflective coatings for a mirror [5]. Thin-layer optics and many devices such as stop-band filters are a well-advanced technology. The use of multi-layer insulating thin films has been successfully developed with band pass filters, reflectors and polarizer’s [6]. Due to their availability, proven reliability and long-term stability, multi-layer dielectric filters are commonly accepted in optical networks. The filters can be made to have excellent wavelength stability, making them ideal filters for passive components. In the fact, dielectric filters are sometimes used to stabilize the wavelength of active ingredients [7]. The optical components consist of multi-layers of High and Low refractive indices material of specific thicknesses, consciousness of the refractive indices and absorption. Multi-layer dielectric filters are based on the concept of multiple reflections that occur between high and low index material interfaces [8].
A dielectric mirror, also referred as a Bragg mirror, is a type of mirror consisting of several thin layers of dielectric material usually deposited on a glass or optical material substrate. This type of a mirror consists of a several thin layers of an insulating material, which is coated on a glass substrate. The behavior of such a mirror depends on the constructive interference between the light reflected from the individual layers. The dielectric mirror can have very high reflection, to better than 99.99%. The dependence of the wavelength of reflection is used to achieve various special types of mirrors, such as a hot mirror which reflects longer wavelengths and is transparent at shorter wavelengths [9]. To reflect a visible light spectrum and transmitted the Infra-Red (IR) wavelengths containing the thermal energy. Cold mirrors are dialectically coated on a glass substrate. Cold mirrors are used to control the thermal energy entering temperature sensitive systems, also have an excellent alternative for transmitting the near infra-red spectrum. Cold mirrors have a sharp cut off between IR and visible light because they have a dielectric coating that can be controlled. Its apposite for hot mirror can be defined as a narrow band multilayer that reflects targeted wavelengths, and transmits visible light. It is a specialized dielectric mirror, a dichroic filter that reflects the entire visible light spectrum while very efficiently transmitting infrared wavelengths [10]. This mirror is based on the concept of multiple reflections between high and low material interfaces [10, 11]. Cold mirrors are used to control thermal energy entering temperature sensitive systems and are also an excellent alternative for transmitting the infrared spectrum. There are many practical uses for cold mirrors, such as copying machines, medical instruments, fiber optic lighting and are often used with tungsten lamps which are the source in a projector or lighting system [6]. Finally cold mirrors can be employed as dichroic beam splitters with laser systems to reflect visible light wavelengths while transmitting infrared. Cold mirrors can be designed for an incidence angle ranging between zero and 45° degrees, and are constructed with multilayer dielectric coatings, in a manner similar to interference filters [12]. In this paper, five groups of materials of: $V_2O_5 \ MgF_2$, SiC $MgF_2$, $TiO_2 MgF_2$ and AlAs $MgF_2$ optical coating instead in one stack is utilized to design cold mirrors has a high reflectance at 550 nm and a low reflectance in IR wavelength at 1100 nm.

2. Simulation Tool

To design interference optical filters open software program "open filter" has been used. This software calculates optical properties of filters and the state of polarization of electromagnetic (EM) radiation that can be expressed by the characteristic matrix of the thin film method for calculating the transmission properties of filters. This software is also utilized to design several multilayer filters [13]. In this program, optimization methods such as injection synthesis is possible (adding an extra layer to give selective transmission) [1 4].

3. Cold mirror design

The behavior of the total multilayer structure is calculated according to the characteristics of the individual layers in the stack when optical filters designing [6]. In this article, colds mirrors designing in the spectrum of 400-2500 nanometer, at the wavelength design 500 nm, by use Open filter software to transmits the spectrum of interest selectively also to reflects the unwanted spectrum in the visible spectrum. It used four groups of materials: $V_2O_5 \ MgF_2$, SiC $MgF_2$, $TiO_2 MgF_2$, and AlAs $MgF_2$ where MgF2 represent low refractive index (1.38) and other material in each group represent a high refractive index $V_2O_5(2.3), SiC(2.69), TiO_2(2.88)$ and AlAs(3.38)[15]. To examine the transmission and reflection of light from layers based on the thickness and form of materials, the open filter uses the transfer matrix method. Using the needle synthesis process, to optimize the transmission of design needed at wavelengths (adding small dense layers called needle and transmission analysis prior to achieving the best results [6].
4. Theoretical approach

A classical optical filter consists of a number of thin layers of \( dj \) thickness and \( Nj \) refractive indices between the incidence and exit media of \( N_{inc} \) and \( N_{ext} \) refractive indices, respectively. By using characteristic matrix method to measure filter optical properties, and discussed in depth in most optical coatings textbook, such as Macleod [16], the \( ith \) layer is represented by:

\[
M = \begin{pmatrix}
M_{11} & M_{12} \\
M_{21} & M_{22}
\end{pmatrix} = \prod_{j=q}^{j} M_j \quad \text{(1)}
\]

Where \( q \) is the multi-layer, and the product is taken in reverse order since the matrices of upper layers must be multiplied on the left.

\[
\begin{pmatrix}
M_{11} & M_{12} \\
M_{21} & M_{22}
\end{pmatrix} = \begin{pmatrix}
cos \delta_H & isin \delta_H / \eta_H \\
isin \delta_H / \eta_H & cos \delta_H
\end{pmatrix} \begin{pmatrix}
cos \delta_L & isin \delta_L \\
isin \delta_L / \eta_L & cos \delta_L
\end{pmatrix} \quad \text{...... (2)}
\]

Where \( \delta_H \) and \( \delta_L \) is phase thicknesses of the High indices, \( \eta_H \), and Low indices, \( \eta_L \) materials respectively. It can be expressed as:

\[
(\delta_j = 2\pi N_j d_j \cos \theta_j / \lambda \quad \text{...... (3)}
\]

Where \( j = H \) or \( L \) and \( \theta_j \) is the angles of refraction in the \( j^{th} \) layer. The refractive index is given by an effective index:

\[
\eta_j = N_j \cos \theta_j \quad \text{...... (4) S polarization state}
\]

\[
\eta_j = N_j / \cos \theta_j \quad \text{...... (5) P polarization state}
\]

\( \eta_j \) is the effective index and \( \theta \) is the angle of incidence.

The amplitude transmission coefficient of the thin layers is:

\[
t = \left( \frac{2 \eta_{inc}}{\eta_{inc} m_{11} + \eta_{ext} m_{22} + \eta_{inc} \eta_{ext} m_{12} + m_{21}} \right) \quad \text{...... (6)}
\]

\[
T = \frac{R_e N_{ext}}{R_e N_{inc}} \quad \text{tt}^* 
\]

\[
T = \frac{R_e N_{ext}}{R_e N_{inc}} |tt|^2 \quad \text{...... (7)}
\]

Where Re is the real part, * denotes the complex conjugate and \( T \) optical transmittance.
5. Results and Discussion

In this research, the stack of design Air \([1.15(0.35H \ L 0.5H)^5 2L]\) glass of cold mirror where \(H\) represents the high quarter wave of optical thickness and \(L\) represent the low quarter wave of optical thickness with \(\lambda=500\) nm. Cold mirror was obtained by using four groups of materials (\(V_2O_5\ \ Mgf_2\ , SiC\ Mgf_2\ , TiO_2\ Mgf_2\ and AlAs\ Mgf_2\)) with a number of layers are12 layer only. The best result as shown in Figure 1 using AlAs\ MgF_2\ with transmission is less than 0.01, so that it has been found at the high variance in refractive indexes i.e., high to low refractive index ratio, sharp cut off between IR and visible light can be achieved and obtained a better optical performance of cold mirror. In all the designs for dielectrics stack of cold mirror, It’s found that optical performance of the AlAs\ MgF_2\ formation shows better results with a desired spectral purity, side part pulses (pass-band oscillations) is low in compared to other groups. Also these mirror formation have a smooth transmitted in the spectral range from 399.5 -786.3 nm and above 800 nm 100% 96.5%, respectively as shown in Figure 1. It can be seen the summary of results for the optical performance at normal incidence angle of multilayers with different groups shown in Table 1.

![Image](image.png)

**Figure 1.** The Optical performance cold mirror at normal incidence using stacks Air \([1.15(0.35H \ L 0.5H)^5 2L]\) glass.

**Table 1.** Optical performance of Multilayers for different groups.

| Multilayers with different Index ratio\((n_H/n_L)\) | Optical performance at normal incidence angle |  
|---|---|---|---|
| | R% over the spectral range at 500nm | T% over the NIR-spectral region at 1100nm |  
| \(V_2O_5(2.3) /Mgf_2(1.38)\) | 100 | 300-668 | 95.8 |
| \(SiC(2.69) /Mgf_2(1.38)\) | 100 | 414-758 | 93.3 |
| \(TiO_2(2.88) /Mgf_2(1.38)\) | 100 | 406-758.077 | 94.2 |
| \(AlAs(3.38) /Mgf_2(1.38)\) | 100 | 399.5-786.3 | 96.58 |

The effect of angle of incident was studied on the optical efficiency of the cold mirror. Where the transmittance has been calculated according to the effects of the incident angles for the materials using
equations (7), as illustrated in Figure 2. It has been noticed weak effect showing of the optical performance of the cold mirror at the angle of incident of un-polarized light is equal to ($\theta = 0^\circ$, $20^\circ$, $25^\circ$, $30^\circ$).

![Figure 2](image_url)

**Figure 2.** The Optical performance cold mirror at incidence angle of $0^\circ$, $20^\circ$, $25^\circ$, $30^\circ$.

When the incident angle of un-polarized light increased ($\theta = 35^\circ$, $40^\circ$ and $45^\circ$) it has been noticed the optical performance of these mirrors becomes better as shown in Figure 3. The angles of incidences are increased, a central spectrum for the cold mirror design changes to the lower wavelengths. At the incident angle of the light increased from $0^\circ$ to $45^\circ$ transmitted range change from 790 to 662nm. Then it’s possible to obtaining a good optical performance of the cold mirror for different angles and is not limited to the angle of incidence of $45$ and zero. For all designs, the optical transmittance is determined by angle of incidence. It can be seen the summary of the results for the optical performance at oblique incident angle of un-polarized light shown in Table 2.
Figure 3. The optical performance cold mirror at incidence angle of 0°, 35°, 40°, 45°.

Table 2. Optical performance for oblique incident angle of un-polarized light.

| Angle of incidence(°) | Transmittance% | S Pol. Waveband (nm) | P Pol. Waveband (nm) |
|-----------------------|-----------------|----------------------|----------------------|
| 20                    | 0-95.5          | (391.8-790.01)       | 0-96.8               | (395-770.2)         |
| 25                    | 0-95            | (385.1-782.3)        | 0-97.2               | (391-758.01)        |
| 30                    | 0-94.4          | (380.2-775.4)        | 0-98.2               | (386-751.4)         |
| 35                    | 0-93            | (375-766.56)         | 0-98.8               | (382-740.2)         |
| 40                    | 0-92.1          | (372.4-764.3)        | 0-99                 | (377-725.1)         |
| 45                    | 0-89.5          | (357-762.86)         | 0-99.8               | (372-694.1)         |

6. Conclusions

Here optical designs of a multilayer cold mirror have been carried out to calculate the optical performance of optimum designing of four groups of materials (V₂O₅ MgF₂, SiC MgF₂, TiO₂ MgF₂ and AlAs MgF₂) with number of layers 12 layer. The stack of AlAs MgF₂ optical coating is optimal design with a desirable spectral purity and small ripples in the transmittance band in compared to other groups and reflects greater than 96.5%, in the visible waveband 399.5-786.3 nm and transmit highly above 800nm. Moreover, the relative phase change between s- and p-polarized and a transmittance band by means of adjusting reflectance and interference orders can be adjusted by varying the index ratio. Finally, it can achieve optimum optical efficiency of a cold mirror for different angles and is not limited to the incidence angles of 45 and zero.

References

[1] Volpian O D and Kuzmichev A I 2013 Russian Journal of General Chemistry 83 (11) 2182.
[2] Kats M A Blanchard R Genevet P and Capasso F 2013 Nature materials 12 (1) 20.
[3] Yeh P 1988 Optical waves in layered media (New York: Wiley).
[4] Yang J M and Kao C Y 2000 In Proceedings of the 2000 Congress on Evolutionary Computation.CEC00 2 978.
[5] Butt M A Fomchenkov S and Khonina S N 2017 In CEUR workshop proceedings 1900 1.
[6] Elyutin V V Butt M A and Khonina S N 2017 3rd International conference ‘Information Technology and Nanotechnology.
[7] Minowa J and Fujii Y 1983 Journal of Lightwave Technology 1 116.
[8] Austin R R 1994 U.S. Patent No. 5,337,191. Washington, DC: U.S. Patent and Trademark Office.
[9] Karaman M Kooi S E and Gleason K K 2008 Chemistry of Materials 20 6 2262.
[10] Rancourt J D 1996 Optical thin films SPIE Press.
[11] Elyutin V V Butt M A Khonina S N 2017 Computer optics and nanophotonics 26.
[12] Li L Sullivan B T and Dobrowolski, J A 1999 U.S. Patent Washington DC: U.S. Patent and Trademark Office (5) 982,541
[13] Butt M A Fomchenkov S A Ullah A Habib M and Ali Z 2016 Computer Optics 40 5 pp 674
[14] Butt M A Fomchenkov S A Kazanskiy N L Ullah A Ali R Z and Habib M 2017 In Optical Technologies for Telecommunications International Society for Optics and Photonics 10342 103420O).
[15] Tropf W J Thomas M E and Harris T J 1995 Devices, Measurements, and Properties 2nd Ed (McGraw-Hill- NewYork).
[16] Macleod H A 2010 Thin-film optical filters 4th Ed (CRC pres Taylor and Francis group).