Optimum Design of high reflection Mirror with ZEMAX

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Abstract. With the aid of ZEMAX-EE software, optimum design of multilayer dielectric mirrors were proposed. Homogeneous dielectric materials TiO2 and SiO2 (as couple) were used to construct the assembly of high reflecting mirror to be operate in the visible and near-IR spectral region (400-800nm) and over angular range (0-65°) of incident of light. Result demonstrate that the omnidirectional reflector was achieved over a wide wavelength band (470-700nm).

1. Introduction

Ultrafast laser technology was one of the main Important trends in the field of laser physics. The pulse laser has ultra-short pulse in picosecond (ps) or femtosecond (fs) [1,2]. Reflector utilized in optical system of ultrashort pulse must possess very high reflection over the entire bandwidth of the pulse. To obtain omnidoirectional reflector for normal and oblique incident of light two methods were used: the first using silver or gold thin sheet as a mirror and the other using all-dielectric materials. The advantage of metallic mirrors is that there is no propagation of light through a dispersive material and the pulse shape remains the same after reflection but reflection is not high enough to use for ultrashort pulse applications [3]. Metallic reflector suffer from absorption which cause damage and completely destroy the assembly and can be used to reflect femtosecond, high-intensity pulses. In compared with ordinary metallic mirrors, all-dielectric mirrors were preferred to use due to extremely low losses (less than 0.01%) at optical and infrared wavelength[4].

Dielectric high reflection mirror probably used for the first time by Penselin and Steudel [5]. They produced for Ti: sapphire laser systems[6] all-dielectric high reflecting mirror with reflectance ~95 % and bandwidth 430-450 nm utilizing thicknesses with harmonic progression. Simple computer-based technique was developed by Baumeister and Stone [7], optimize the reflectance of multilayer reflector to ~94% over wavelength band (500-510nm). Computer design and refinement of reflectors was described by Pelletier et. al. [8] in 1971, result indicate that ripple was appear in high reflection zone within 95.5–98 % over a wide spectral wavelength 400-800nm.

Rashid and Ali 2016 [9], adopting ZEMAX software supported with Teraplot software to design and investigate one dimension photonics crystal (Distributed Bragg Reflector DBR) based on multilayer concept to be operate in visible spectral region.

Recently Rashid et al 2017[10], adopt Transfer matrix method (TMM) to supported with Teraplot software to achieve optimum design complete wideband omnidirectional Bragg reflector (1D-photonic omnidirectional reflector) to be applied in IR spectral region (8-14μm).
2. Theory of Thin Films

According to the Fresnel equation in air [11, 12]. The reflectance of a quarter wave stacks at oblique incidence is given by [13].

\[ R = \frac{n_0 - Y}{n_0 + Y} \left( \frac{n_0 - Y}{n_0 + Y} \right)^* \]  

(1)

The name “effective index of refraction of air \( \eta_0 \)” were previously introduced by the theory of a thin optical layer [14, 15]. The input optical admittance of assembly \( Y \) was introduced [16] and given by:

\[ Y = \frac{n_b}{E_a} \]  

(2)

Where \((E_a & H_a)\) are the electric and magnetic fields input. \(E_a\) and \(H_a\) are continuous across a boundary due to Maxwell's equation. At the incident interface, the tangential components of \(E_a\) and \(H_a\) connect with the tangential components of \(E_b\) and \(H_b\) at the final interface.

\[ \begin{bmatrix} E_a \\ H_a \end{bmatrix} = \begin{bmatrix} \cos \delta & i \sin \delta / \eta_r \\ i \eta_r \sin \delta & \cos \delta \end{bmatrix} \begin{bmatrix} E_b \\ H_b \end{bmatrix} \]  

(3)

Equation (3) at the incident interface known as the Transfer matrix of the film [17] which is \(2 \times 2\) matrix.

\[ \begin{bmatrix} E_a \\ H_a \end{bmatrix} = \prod_{r=1}^{q} \begin{bmatrix} \cos \delta_r & (i \sin \delta_r / \eta_r) \\ i \eta_r \sin \delta_r & \cos \delta_r \end{bmatrix} \begin{bmatrix} E_b \\ H_b \end{bmatrix} \]  

(4)

Figure 1, show the multilayer model [18].

![Multilayer model notation](image)

**Figure1.** Multilayer model notation [18].

Effective index of refraction \( \eta \) relative to the state of polarization of the radiation \( p \) (TM mode) and \( s \) (TE mode) that crosses were[15]:

\[ \eta_p = n / \cos \theta, \]  

(5)

\[ \eta_s = n \cos \theta, \]  

(6)
"n" is the refractive index of the layer; "θ" is the angle of refraction under the light passes through the layer obtained from the Snell's Law:

\[ n_0 \sin \theta_0 = n \sin \theta \]  

(7)

Using the Snell law, then, \( \cos \theta = \left[1 - A^2 / n^2 \right]^{1/2} \), where \( A = n_0 \sin \theta_0 \) (A is called numerical aperture). The "effective thickness" result from the multiplication of optical thickness of each layer times by \( \sin \theta \). \( n_0 \) and \( \theta_0 \) are the index of refractive of incident medium (air) and angle of incidence, respectively. \( \eta_p \) and \( \eta_s \) are then:

\[ \eta_p = n \left[1 - A^2 / n^2 \right]^{1/2} ; \]  

(8)

\[ \eta_s = n \left[1 - A^2 / n^2 \right]^{1/2} ; \]  

(9)

The "effective thickness" is then:

\[ \delta_q = \frac{4n}{\lambda} \eta_q d_q \cos \theta \]  

(10)

Where "d" is the thickness of the layer (geometrical), \( \theta \) is the angle of refraction.

3. Result and Discussion

3.1. Effective Refractive Index of Dielectric Materials

Figure 2, depict the variation of the effective index of five commonly used materials versus the angle of incident and index of refractive. Figure clearly demonstrates the influence of angle variation on the amount of splitting between the orthogonal polarizations. The indices of refraction used in design are 1.00 (air) in color blue, 1.46 (SiO_2) in color celestial, 1.63 (Al_2O_3) in green color, 2.58 (TiO_2) in color purple [19-21], and (1.52) BK7 glass in red color. Furthermore, the figure also indicates that materials with high refractive index split the orthogonal polarization less than materials with low index ones further, \((\eta_p or \eta_{TE})\) and \((\eta_s or \eta_{TM})\) curves shows linear behavior of positive slope.

3.2 Design Using Multilayer Dielectric Coatings

ZEMAX software package was used as an optical coating package [22]. The selected dielectric materials were TiO_2 "High" and SiO_2 as "Low" index with quarter wave optical thickness at the design
wavelength ($\lambda_0=0.6328$ $\mu$m) deposited on BK7 optical glass ($n_{\text{glass}}=1.52$). The proposed design construction is $\text{Air}\ [\{HL\}^5 H]\ \text{Glass}$, the reflectance vs. wavelength and reflectance vs. incident angle of multilayer dielectric mirror was shown in figures 3 & 4. This design was used as a good "initial design" implemented in the second step.

Figure 3. Reflectance vs. Wavelength for initial design of multilayer dielectric mirror: air$\ [\{HL\}^5 H]\ \text{glass}$, at ranges (a) (0.400-0.800) $\mu$m, (b) (0.470-0.700) $\mu$m, at design wavelength 0.6328 $\mu$m and angle incident 45°.

Figure 4. Reflectance vs. Incident angle over the range (0-65°) for initial design multilayer dielectric mirror: air$\ [\{HL\}^5 H]\ \text{glass}$, at design wavelength 0.6328 $\mu$m.

3.3 Optimum Design of Multilayer Dielectric Coatings

Adopting ZEMAX software layer thickness was optimize the thickness for the proposed design construction [part (3.2)] using "Hammer optimization". The layer thickness was change from operand "CODA" that constrain the coating multiplier. An exhaustive searching for optimum solution included with ZEMAX enriched with a merit function of least squares form [23]:
\[ MF = \left[ \frac{\sum W_i(V_i - T_i)^2}{\sum W_i} \right]^{1/2} \] (11)

Where \( W \), \( V \) and \( T \) represent the "weight of the operand", "current" and "target" values (the absolute value) and \( i \) indicates the operand number. Controlling the values of target and weight, the program arrived at the design \( R \sim 100 \) shown in figures 5 & 6. The spectral reflectance shows that multilayer dielectric mirror operating over a wide spectral wavelength (0.47-0.7\( \mu \)m) and angular view range (0\(^\circ\)-65\(^\circ\)). The final optimum physical thicknesses (in quarter-wave effective thickness at 45\(^\circ\)) is:

\[
\begin{array}{cccccccccccc}
\text{Air} & 0.1790H & 0.1847L & 0.1847H & 0.1847L & 0.1847H & 0.1846L & 0.1846H \\
0.1889L & 0.3048H & 0.1851L & 0.3782H & 0.4495L & 0.286H & 0.226L & \\
0.2247L & 0.2184H & & & & & & \\
\text{Glass} & & & & & & & \\
\end{array}
\]

**Figure 5.** Reflectance vs. Wavelength for optimum design of multilayer dielectric mirror at ranges (a) (0.400-0.800) \( \mu \)m, (b) (0.470-0.700) \( \mu \)m, at design wavelength 0.6328 \( \mu \)m and angle incident 45\(^\circ\).

**Figure 6.** Reflectance vs. Incident angle over the range (0-65\(^\circ\)) for optimum design of multilayer dielectric mirror at design wavelength 0.6328 \( \mu \)m.
4. Conclusions
In this article, a reliable strategy for designing of omnidirectional reflector with ZEMAX was presented. In this respect, we have established the relationship of changing effective refractive index with both index and incident angle of light then how to utilize numerical optimization to reach optimum design which requires building algorithm of targets and weights including layer. Results show that ($R=100\%$) of spectral width ~230nm within spectral wavelengths range (0.47-0.7μm) and angular view range (0-65°). Further, this algorithm reaming valid and efficient with the same design structure for other spectral bands centered at different wavelength and angles.

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