Theoretical Design of an Antireflection Coating for near Infrared Region (800-1500 nm) for glass substrate

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Abstract. The main purpose of this research is to design multilayer filter that can permit the IR wavelength (800-1500 nm), to make the aim of the research comes true, the equations of multilayer system have been derived and developed, and then a program code has been made using FORTRAN language. The films thicknesses of the multilayer could be even quarter wavelength or unlimited. The research results illustrated that the best design when the stack number equals to(6).

1 - Introduction
The design of broadband antireflection (BBAR) coatings is established upon the indicator of refraction of the materials to be used, the bandwidth wanted, the overall thickness of the coating, and the number of layers. In the design of a BBAR for multilayer coating, there are four operators which effect the consequences [1,2]. The refractive indices of the multilayer for materials used. The bandwidth over which the reflection is to be decrease. The overall thickness of multilayer the coating. The number of layers in the design. The bandwidth is usually specified overall thickness and number of multilayer as variables. The choice of materials is limited by the spectral range of interest and the environmental resistance desired—we have confined the multilayer materials used here to indices of 2.49 and 1.37. It will be confirm here that there are clear lower limits on the overall thickness and number of layers for an eclecticism design, and that it is unfanorable to surpass a certain upper range of overall thickness and the minimum number of layers for a given design problem[3-5]

2. Theoretical Aspect Multiayer equations
Optical interference effects can be characterized as either constructive or destructive interference, where the phase shift between interfering wave fronts is 0 or 180 degrees respectively. For two wave fronts to completely cancel each other, as in a single-layer antireflection coating, a phase shift of exactly 180 degrees is required. Where three or more reflecting surfaces are involved, full repeal can be carried out by narrowly selecting the relative phase and intensity of the interfering beams (i.e., optimizing the relative optical thicknesses). This is the basis of a two-layer antireflection coating, where the layers are adjusted to suit the refractive index of available materials, instead of vice versa. For a given integration of materials, there are usually two combinations of layer thicknesses that will give zero reflectance at the design wavelength. These two combinations are of different overall thickness. For any kind of thin-film coating, the thinnest contingent overall coating is hired because it will have best mechanical properties (less stress)[6,7]. A thinner combination is also less wavelength sensitive.
The basic function for designing multilayer systems is to find the values of the construction parameters including refractive indices, extinction coefficients and thicknesses that bring the computed optical performance close to the target allotment over the coveted wavelength band [8-12]. The mathematical assumptions used in this study are:

- The radiation is incident normally on the materials layers.
- The extinction coefficient of all materials equal to zero. It is mean that all used materials are non-absorbing materials for the incident wavelength.
- The mathematical reflectance (Rcomp) and transmittance (Tcomp), which measure the energy reflected from or transmitted through the films, respectively, are given by (1):

\[
R_{\text{comp}} = \left( \frac{(E_r)_0}{(E_t)_0} \right)^2, \quad T_{\text{comp}} = \frac{n_m}{n_0} \frac{1}{|{(E_t)_0}|^2}\]

(\(E_r)_0\) and (\(E_t)_0\) are the reflected and transmitted electric field amplitudes at the incident medium, respectively. (\(n_0\)) and (\(n_m\)) are the refractive index of the incident medium and substrate, respectively. The basic recursion relation for the reflected and transmitted electric field amplitudes for all layers is:

\[
\left( \frac{(E_t)_{j+1}}{(E_r)_{j+1}} \right) = \frac{1}{2} \left( 1 + \frac{n_j}{n_{j-1}} \right) e^{i\phi_j} \left( 1 - \frac{n_j}{n_{j-1}} \right) e^{-i\phi_j} \left( \frac{(E_t)_j}{(E_r)_j} \right) \]

\(\phi_j = \frac{2\pi}{\lambda} n_j d_j\)

(\(n_j\) and \(d_j\)) are the refractive index and the thickness of layer (j) of the coating system. The procedure to compute the reflectance or the transmittance for the multilayer system is to apply equation (3) recursively, starting at the bottom-most layer, i.e., \(j=m\) (substrate), backward to layer \(j=0\) (incident medium).

3. Materials choosing

3-1: The material selection:

The designing of (BBAR) depends on the materials that can deposit on the glass surface in order to make the reflectance and transmittance equal to the designing values at the desired wavelength.

To make the desired designing for reflectance and transmittance, one can choose some proper materials as a thin film via evaporating them on the substrate material. The choosing of thin film materials must verified some basic aspects:

- Maximum transmittance at the desired region of wavelengths.
- Minimum extinction coefficients
- Availability and low cost.

The most suitable materials that can be found using the text materials books are (MgF2 and TiO2). The refractive index for (MgF2) as a function to wavelength is:

\[
n^2 = 1 + \frac{0.48755108 \lambda^2}{\lambda^2 - (0.04338408)^2} + \frac{0.39875031 \lambda^2}{\lambda^2 - (0.09461442)^2} + \frac{2.3120353 \lambda^2}{\lambda^2 - (23.793604)^2}\]

The formula is valid for the range of wavelength (0.2 - 7.0 \(\mu m\)). While the formula of the refractive index of (TiO2) is:

\[
n^2 = 5.913 + \frac{0.2441 \lambda^2}{\lambda^2 - (0.28337)^2}\]

Which is valid for the range of wavelength (0.43 - 1.5 \(\mu m\)). In both equation the wavelength in unit of micrometer. Figure 1 represents the refractive indices for both materials as a function for wavelengths.

Which is valid for the range of wavelength (0.43 - 1.5 \(\mu m\)). In both equation the wavelength in unit of micrometer. Figure 1 represents the refractive indices for both materials as a function for wavelengths.
As shown from Figure 1, the mean value of refractive index for TiO2 is equal to 2.49030, while the mean value for MgF2 is equal to 1.37488

3-2: Layers distribution:

The materials will distribute as stack with same layers as:

Air / MgF2, TiO2, MgF2, TiO2, MgF2, TiO2… / glass

Or in the simple form: Air / m (MgF2, TiO2) / glass, where is (m) is the stack number.

4. Results and Discussion

The first design with stack number equals to (2), the thicknesses of the layers are shown in Table 1, while the reflectance spectrum is shown in Figure 2 the total optical path equals to (0.880 um), the mean reflectance for the invisible wavelength region (0.4-0.7 um) equals to (4 %), while the maximum reflectance for IR region (0.8-1.5 um) equals to (70 %).

| Stack number=2 |
|----------------|
| material | Ref. index | Thickness (um) |
|-----------|------------|----------------|
| 1         | Air        | 1.00000        | --------     |
| 2         | MgF2       | 1.37488        | 0.07078      |
| 3         | TiO2       | 2.49030        | 0.09989      |
4  MgF2     1.37488     0.19369
5  TiO2     2.49030     0.10772
6  glass    1.52000     ----------

Total (nd)  0.880603

**Figure. 2** Reflectance spectrum versus wavelength for stack number=2

**4-1: The stack number=3**

In table .2, observe when increase thicknesses of the layers, the reflectance spectrum increasing also shown that in Figure. 3 the total optical path equals to (1.449388um), the mean reflectance for the invisible wavelength region (0.4-0.7.5 um) equals to (6 %), while the maximum reflectance for IR region (0.8-1.6 um) equals to (88 %).

**Table 2.** The optical properties

| Stack number =3                  |
|----------------------------------|
| material   | Ref. index | Thickness (um) |
|------------|------------|----------------|
| 1          | Air        | 1.00000        | ---------     |
| 2          | MgF2       | 1.37488        | 0.09802       |
| 3          | TiO2       | 2.49030        | 0.10510       |
| 4          | MgF2       | 1.37488        | 0.19189       |
Figure 3. Reflectance spectrum versus wavelength for stack number=3

Also found the behavior of changing the thickness values of the layers show in tables (3,4,5,6 and 7 ), give rise to the reflectance spectrum is differences in peak values in Figures (4,5,6,7 and 8), the total optical path equals to (2.230514um, 2.696393um, 3.178093um, 3.800721um, and 4.582815um) respectively, while the maximum reflectance for IR region (0.8-1.6 um) equals to (92 %, 95%, 97%, 98%, 100% ) respectively.

4-2: The stack number=4

Table 3. The optical properties

| Stack number | material | Ref. index | Thickness (um) |
|--------------|----------|------------|----------------|
| 1            | Air      | 1.00000    | ----------     |
| 2            | MgF2     | 1.37488    | 0.09044       |
| 3            | TiO2     | 2.49030    | 0.11520       |

| Total (nd) | 1.449388 |

Also found the behavior of changing the thickness values of the layers show in tables (3,4,5,6 and 7 ), give rise to the reflectance spectrum is differences in peak values in Figures (4,5,6,7 and 8), the total optical path equals to (2.230514um, 2.696393um, 3.178093um, 3.800721um, and 4.582815um) respectively, while the maximum reflectance for IR region (0.8-1.6 um) equals to (92 %, 95%, 97%, 98%, 100% ) respectively.
Table 4. The optical properties

| Stack number = 5 |
|---|---|---|
| material | Ref. index | Thickness (um) |
| Air | 1.00000 | -------- |

Figure 4. Reflectance spectrum versus wavelength for stack number=4.

4-3: The stack number=5
2  MgF2  1.37488  0.09370
3  TiO2  2.49030  0.11431
4  MgF2  1.37488  0.32562
5  TiO2  2.49030  0.12081
6  MgF2  1.37488  0.19469
7  TiO2  2.49030  0.10387
8  MgF2  1.37488  0.18644
9  TiO2  2.49030  0.10169
10 MgF2  1.37488  0.18126
11 TiO2  2.49030  0.10009
12 glass 1.52000  -------

Total (nd)  2.696393

**Figure 5.** Reflectance spectrum versus wavelength for stack number=5.

**4-4:** The stack number=6
### Table 5. The optical properties

| Stack number = 6 |
|------------------|
| material | Ref. index | Thickness (um) |
|----------|-------------|----------------|
| 1        | Air         | 1.00000       | ----------    |
| 2        | MgF2        | 1.37488       | 0.09094      |
| 3        | TiO2        | 2.49030       | 0.11546      |
| 4        | MgF2        | 1.37488       | 0.32537      |
| 5        | TiO2        | 2.49030       | 0.11901      |
| 6        | MgF2        | 1.37488       | 0.19711      |
| 7        | TiO2        | 2.49030       | 0.10479      |
| 8        | MgF2        | 1.37488       | 0.18367      |
| 9        | TiO2        | 2.49030       | 0.09563      |
| 10       | MgF2        | 1.37488       | 0.16815      |
| 11       | TiO2        | 2.49030       | 0.09851      |
| 12       | MgF2        | 1.37488       | 0.18953      |
| 13       | TiO2        | 2.49030       | 0.10524      |
| 14       | glass       | 1.52000       | ----------    |
|          | Total (nd)  |                | 3.178093     |
Figure 6. Reflectance spectrum versus wavelength for stack number=6.

4-5: The stack number=7

Table 6. The optical properties

| Stack number =7 |
|------------------|
| material | Ref. index | Thickness (um) |
|          |            |                |
| 1        | Air         | 1.00000        | -------- |
| 2        | MgF2        | 1.37488        | 0.09612  |
| 3        | TiO2        | 2.49030        | 0.12454  |
| 4        | MgF2        | 1.37488        | 0.32072  |
| 5        | TiO2        | 2.49030        | 0.11860  |
| 6        | MgF2        | 1.37488        | 0.21808  |
| 7        | TiO2        | 2.49030        | 0.11283  |
| 8        | MgF2        | 1.37488        | 0.19655  |
Table 7. The optical properties

| Stack number =8 | material | Ref. index | Thickness (um) |
|-----------------|----------|------------|----------------|
| 9               | TiO₂     | 2.49030    | 0.10621        |
| 10              | MgF₂     | 1.37488    | 0.18865        |
| 11              | TiO₂     | 2.49030    | 0.10016        |
| 12              | MgF₂     | 1.37488    | 0.17167        |
| 13              | TiO₂     | 2.49030    | 0.09810        |
| 14              | MgF₂     | 1.37488    | 0.18815        |
| 15              | TiO₂     | 2.49030    | 0.10391        |
| 16              | glass    | 1.52000    | -------        |
|                 |          |            | Total (nd) 3.800721 |

Figure 7. Reflectance spectrum versus wavelength for stack number=7

4-6: The stack number=8
|   |     |       |       |
|---|-----|-------|-------|
|   | Air | 1.00000 |       |
| 2 | MgF2 | 1.37488 | 0.09430 |
| 3 | TiO2 | 2.49030 | 0.11336 |
| 4 | MgF2 | 1.37488 | 0.34445 |
| 5 | TiO2 | 2.49030 | 0.11282 |
| 6 | MgF2 | 1.37488 | 0.19652 |
| 7 | TiO2 | 2.49030 | 0.25157 |
| 8 | MgF2 | 1.37488 | 0.17869 |
| 9 | TiO2 | 2.49030 | 0.09800 |
|10 | MgF2 | 1.37488 | 0.18435 |
|11 | TiO2 | 2.49030 | 0.10134 |
|12 | MgF2 | 1.37488 | 0.17196 |
|13 | TiO2 | 2.49030 | 0.09762 |
|14 | MgF2 | 1.37488 | 0.18201 |
|15 | TiO2 | 2.49030 | 0.10411 |
|16 | MgF2 | 1.37488 | 0.19003 |
|17 | TiO2 | 2.49030 | 0.10994 |
|18 | glass | 1.52000 |       |
|   | Total (nd) | 4.582815 |       |
5. Conclusions

It has been our trial that the more powerful of a starting design for a BBAR coating, other than one of only a few layers, tends to reach a result at a local minimum which is not all occasion the better that can be done in the general region of obtainable variable parameters. The number of layers are given by the designer to the optimization program, and the more powerful is only on the thicknesses of the layers.

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