Optimization Approach of Multilayer (Metal-Dielectric) Pass Band Filter

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Abstract. This study presents new construction design stacks for optimal narrow pass filters in two different spectral regions. The new design of narrow pass band filters have optimal specifications as narrow pass band, high transmittance, and zero transmittance at stop band along wide range of wavelength. Procedures were given to design such filters by adjusting metal with dielectric materials. We investigated the construction stacks to have proper number of coating layers with controlling the thickness of each layer.

1. Introduction
Optical thin-film coating technology is very important to modern optics and its applications such as in spectroscopy, medicine, astronomy, communication etc. [1]. It can be described as any device or material is used to change the spectral intensity distribution or the state of polarization of the electromagnetic radiation for satisfying performance specifications [2,3].

These optical coatings consist of multilayer thin films materials deposited on substrate, and have the property of being able to reflects and transmits range of wavelengths. Optical interference filter is the preferred type of optical coatings, which use interference to achieve the demanded optical performance [4,5]. These filters are made great progress to enable effects such as band pass, edge filters, beam splitter and others [6].

There are two types of multilayer coatings: dielectric and metal- dielectric. Design and fabricate dielectric coatings have a high optical performance requires deposition of a sequence of two (or more) different dielectric materials with well-controlled thickness, forming a stack of many layers. To get effective performance, usually required many layers and this complicates fabrication process [7]. Adding metal layers extend the versatility of multilayer coating design, these layers can for example reduce unwanted reflections which occur from rejected bands such as those occurring in band pass filters [8].

An optical band pass filter selectively reflects or transmits specific wavelengths, and has a wide range of applications, including display, optical communications, and sensing band pass filters can be divided into two types broad-band-pass and narrow-band-pass filters, the classification is depending on the design rather than on the actual width of the pass band [9,10].

Narrow band pass (NBP) filters have historically been made of layers which are a quarter wave optical thickness (QWOT) at the design wavelength λ₀, in which has high transmittance in a narrow wavelength region (λ₁ to λ₂) and high rejection (low transmittance which mean high reflectance) in all other wavelength regions (λ < λ₁ and λ > λ₂) as it is shown below in Figure 1[11,12].
Figure 1. Narrow band pass (NBP) filter (adapted from [9])

In this study, an optimised narrow band pass filter design was attempted. It consists of metal-dielectric layers of suitable thickness for best optical performance. Silver was chosen for metal layers because it has low residual absorption loss around 4%. The theoretical analysis was performed using the characteristic matrix approach, a suitable computer program was written in matlab for this purpose. A very narrow band pass filter was achieved with 80% transmittance in pass band range and 0% transmittance in each of the stop bands.

2. Theoretical principals of Characteristic Matrix
This study depended on calculations Characteristics Matrix to determine the spectral transmittance profile for multilayer structures on a substrate. This approach is used to calculate optical performance, i.e., (transmittance and absorbance) of an assembly of thin films layers. A program written in Matlab for this purpose.

Characteristics matrix are assembly of q thin film layers, simply characteristic matrix is product the individual matrices for the individual layers of assembly taken in the correct order, given by [13]:

\[
\begin{bmatrix}
C \\
B
\end{bmatrix} = \prod_{r=1}^{q} \begin{bmatrix}
\cos \delta_r & (\sin \delta_r)/n_r \\
(n_r \sin \delta_r) & \cos \delta_r
\end{bmatrix}
\]  

(1)

where, C and B are normalized total tangential electric and magnetic fields respectively at the input surface.

\[\delta_r = 2 \pi n_r d_r/\lambda]\n
\(n_r, d_r\) are refractive index and physical thickness of layer

q is the number of layers next to substrate

\(n_s\) is the refractive index of the substrate.

\(\begin{bmatrix}
B \\
C
\end{bmatrix}\) is defined as the characteristic matrix of the assembly.

According to the characteristic matrix details the transmittance (T) and absorbance (A) of the multilayer system are given as follows:

\[
T = \frac{4n_s \text{Re}(n_s)}{(n_s B + C)(n_s B - C)}
\]

(2)

\[
A = \frac{4 \text{no} (BC - n_s)}{(n_s B + C)(n_s B + C)^*}
\]

(3)

\text{Re}(ns) represents to real part of refractive index of substrate.
3. Designs and Discussion
In this section narrow band pass filters depending on using metallic-dielectric materials were submitted. Optimal performance of these filters were gotten with appearance of new construction stacks involved promising materials.

The preparation of the construction stacks of multilayer coatings were maintained to have small total thickness within agreement range for fabrication processes. certainly we were attentive to get designs with very low absorbance as the metal had been used. Optical behaviour of designs covered wide ranges of wavelengths including visible and near-IR regions.

Figure 2 demonstrates the behaviour of innovative design of narrow band pass filter depending on metallic-dielectric materials structure. the construction stack consisting of TiO$_2$ as a high refractive index material is referred by H layers and SiO$_2$ as a low refractive index material is referred by L layers. multilayer coating stack deposited on glass as substrate for visible range (450-750 nm) and design wavelength $\lambda_o=550$nm.

As it has been mentioned silver is suitable metal in the visible region which has a low absorption loss, so it has been used to accomplish the optimal performance. For case of Ag refractive index is equal to $(0.055 - 3.32)$ for visible region, also the average physical thickness of Ag layers within stacks is less 24 nm.

In this design we got relatively narrow pass band with the pass band width less than 50 nm, the peak of the transmittance is high reaches to 80% the optimized performance in stop band (blocking range) was obtained.

![Figure 2](image.png)

Figure 2. The optical performance of metal–dielectric narrow band pass filter of construction:

\[
\text{Ag//0.794027407L\ 0.96431162791H\ 1.9702232558L\ 0.964211679H\ 1.12566588L//Ag//1.0431069767H//Glass}
\]

We took into consideration the adjusting of coating layers thickness with utilising suitable coating materials and try to get small overall thickness of construction stacks which is important in manufacturing.

Also, we attended to get filter design that has low absorbance and obtained progress in optical performance of narrow band pass filter, absorbance behaviour of such design demonstrated in Figure 3.
Figure 3. Absorptance behavior of metal –dielectric narrow band pass filter for construction design in Fig.2 along visible region.

Another design of narrow band pass filter was submitted for visible region at design wavelength $\lambda_0=550$ nm. Figure 4 demonstrates such design, it is obvious optimal performance was obtained.

The feature of this design that it is consisting of new dielectric-materials in which the construction design stack is prepared by adjusting of ZrO$_2$ as a high refractive index material is referred by H layers and MgF$_2$ as a low refractive index material is referred by L layers deposited on glass as substrate.

A good advantage of this design is been obtained that the average physical thickness of Ag layers within stacks is less than 20 nm, furthermore the absorptance of design stack is low as shown in Figure 5. Almost this design have same construction stack of the previous one but with different coating layers and smaller total thickness.

However the design presents the ability to adjust different dielectric materials with Ag to get narrow band pass filter for the same region. The controlling of the layers thickness is prompting to enhance the optical performance of designs.

Figure 4. The optical performance of metal –dielectric narrow band pass filter of construction:

| Ag //0.734027407L/0.9642162791H1.9801232568L0.8943149791H1.23566598L//Ag //1.0331068747 H/Glass | Transmittance | Wavelength (nm) |
|---|---|---|
| | | 450 | 550 | 650 | 750 |
| | 0 | 10 | 20 | 30 | 40 |
| | 50 | 60 | 70 | 80 | 90 | 100 |
Figure 5. Absorptance behavior of metal–dielectric narrow band pass filter for construction design in Fig.4 along visible region.

Optimized optical performance metal–dielectric narrow band pass filter is obtained for near-IR region (700-1000 nm). Highest efficiency of design is shown in Figure 6, that involves the narrow pass band is not wider than 15 nm, transmittance peak is reach to 80%, and the better behavior in stop band with zero transmittance along more than 100 nm at the two sides of pass band. For this region we utilized construction stacks consisting of TiO₂ as a high refractive index material is referred by H layers and SiO₂ as a low refractive index material is referred by L layers. multilayer coating stack deposited on glass as substrate with design wavelength λ₀=850nm. For Ag refractive index is equal to (0.04–i6.4) for near-IR region, also the average physical thickness of Ag layers within stacks is less 23 nm. The absorptance is very low almost non take in account as it is shown in Figure 7.

Figure 6. The optical performance of metal–dielectric narrow band pass filter of construction: Ag/0.80428408L/0.97431162681H/1.980022558L/0.9421761H/1.11586588L/Ag/Glass
Figure 7. Absorptance behavior of metal–dielectric narrow band pass filter for construction design in Fig.3 along near IR region.

This is another progress in design was archived, where it has been used the same dielectric materials with Ag for visible and near-IR regions. Another trick adopted here is by preparing the same construction stack for visible and near-IR regions. However, the specific optical performance of narrow band pass filter for the two regions was achieved by controlling thickness of each layer and adjusting them with accomplished layers of Ag. It should mention that the absorptance of designs is low for the two regions which is important to get more efficient and practical filters.

4. Conclusions
This manuscript includes designs of optimized narrow band pass filters for visible and near-IR regions. The results showed optimal optical performance where they are characterized by nearly narrow pass band with transmittance reach to 80%, zero transmittance on both sides of the pass band with elimination of absorptance by adopting innovative construction stacks depending on silver as metal adjusting with specific dielectric materials.

It should be mentioned to the strategy of controlling the thickness of each layer and how much it is effective to get sophisticated designs of optimal performance for two different regions. We employed a suitable number of layers with controlling the thickness of each layer tried to get small overall thickness. This work is a huge progress where it had been included the using of same (metallic-dielectric materials system) to get narrow band pass filter for two different regions. Also, Ag shows an advanced behavior as a good metal layer that enhances designs performance for visible and near-IR regions.

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