Design of Narrow Bandpass Filters using Thin Films

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ABSTRACT

Design of optical thin film filters requires a model to predict the optical performance of a given multilayer. A simple and fast way to compute the reflectance and transmittance of any arbitrary thin film assembly is given by the Abeles method, wherein the characteristics of each layer is fully described by a 2x2 matrix. The two design methods for narrow bandpass filters in the visible spectrum were discussed. Several design procedures were outlined.

INTRODUCTION

Optical equipment consists, in part, of optical surfaces that control and modify the light passing through the instruments. The performance of such devices will ultimately depend on the efficiency of such surfaces. However, real optical surfaces partially transmit, reflect and scatter light to an extent that is sometimes detrimental to the equipment's performance.

For instance, zoom lenses used in photography are made up of a compound lens that would be completely unusable without some form of antireflection coating. Gain flatteners, edge filters and bandpass filters are also very important for the telecommunication industry.

An optical thin-film filter consists of a series of optical surfaces that modify light as it passes through it. In designing these films, it is required to find an arrangement of suitable layers exhibiting specified properties. The reflectance, transmittance and sometimes absorbance must then be altered by the film to meet these specifications.

The performance of a particular thin-film design is determined by the interference that occurs because of the reflected light at various interfaces within the coating. The relative phases of the combined beams are determined by the thickness and indices of the various layers while the amplitude is determined by the properties of the materials on either side of the interface.

THE THEORY

The calculation of the interference of an assembly of thin-films can be done in various ways. Most methods, such as the film mode matching (FMM), though rigorous and more accurate, are numerically complicated and thus impractical (Escoubas et al 2001). The most universally adopted calculation method was formulated by Abeles. It involves a two-stage process in which the electromagnetic fields in the film are reduced into positive and negative going partial waves.

In all the calculations, the film layers are assumed to be homogeneous and isotropic slabs that have particular refractive indices \(n\) and extinction coefficients \(k\). Both \(n\) and \(k\) may vary with wavelength (dispersion). The surfaces of each layer are considered smooth and parallel. This

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may seem to be a considerable oversimplification of real thin-film assemblies. Actual films have rough surfaces that may not be perfectly parallel to one another. Additionally, the interface between layers may exhibit lattice mismatch, leading to stress and planar defects. However, it has been found that the model works exceedingly well in practice, attributing to its extensive use in the design and analysis of optical thin-film filters.

The equations governing an arbitrary wave passing through on the thin film surface can be quite complex. However, it is sufficient to consider two special cases; when the electric field is perpendicular to the plane of incidence (s-polarization) and when it is parallel (p-polarization). A plane wave polarized in an arbitrary direction can be represented by a combination of these cases (Thelen 1989). The relationship between the electric and magnetic fields incident to the film interface at given angle $\alpha$ is given by,

$$E(z_1) = E(z_2) \cos \phi + \frac{z_0 H(z_1) i \sin \phi}{n}$$

$$z_0 H(z_1) = E(z_2) i \sin \phi + z_0 H(z_2) \cos \phi$$

where

$$z_0 = \sqrt{\frac{\mu_0}{\epsilon_0}}$$

$$n_{s-pol} = n \cos \alpha$$

$$n_{p-pol} = n \cos \alpha$$

$$n_0 \sin \alpha_0 = n \sin \alpha$$

$\phi$ = phase thickness of the layer

$z_1$ = interface between the solid and the film

$z_2$ = interface between the film and the substrate

These equations can be further simplified by reducing them into a matrix form,

$$\begin{bmatrix} E(z_1) \\ z_0 H(z_1) \end{bmatrix} = \begin{bmatrix} \cos \phi & \frac{i \sin \phi}{n} \\ i \sin \phi & \cos \phi \end{bmatrix} \begin{bmatrix} E(z_2) \\ z_0 H(z_2) \end{bmatrix}$$

Evaluation of these matrices will permit the calculation of the reflectance and transmittance of any arbitrary thin film assembly.

**DESIGN OF NARROW BANDPASS FILTERS (NBF)**

The simplest design for a narrow bandpass filter is that of a Fabry-Perot Inferometer. This takes the form of |reflector|spacer|reflector|. It has already been mentioned that an alternating high index - low index stack will have a high reflectance at the design wavelength. An all dielectric Fabry-Perot Inferometer can then be realized by either, 

$$\text{HLHL...L HH L...LHLH} \Rightarrow (HL)^p \ 2H \ (LH)^f$$

Or

$$\text{HLHL...H LL H...LHLH} \Rightarrow (HL)^p H \ 2L \ H(LH)^f$$
Figure 1 a) Transmittance of an all-dielectric Fabry-Perot interferometer. (b) Transmittance of a DHW filter. TiO\textsubscript{2} and SiO\textsubscript{2} are used for H and L respectively (n\textsubscript{TiO\textsubscript{2}} = 2.385, n\textsubscript{SiO\textsubscript{2}} = 1.445). Design angle is 550nm.

The transmission curve of these types of filters consists of a very sharp peak at the design angle. For most applications, such a shape is undesirable. Rather, a more rectangular shape is required with the high transmission zone extending over a range of wavelengths. This can be achieved by coupling a coupling two Fabry-Perot filters in series with each other. This type of filter is called a *Double Half-Wave (DHW)* filter or a *Two-Cavity filter*.

Figure 1 shows the transmittance profile of an all dielectric Fabry-Perot filter and a DHW filter using TiO\textsubscript{2} and SiO\textsubscript{2}. Edge filters or adsorption filters can latter be used to flatten the transmittance on either side of the high transmission zone.

Addition of more half-wave layers will increase the steepness between the stop regions and the pass regions. Unfortunately, the rippling within the high-transmission zone increases as the number of cavities is increased. Figure 2 shows several cavity filter designs. It can be seen that 4-cavity filter still has acceptable rippling while the 5-cavity filter is unusable.

Figure 2. A (a) 3-cavity filter (b) 4-cavity filter and a (c) 5-cavity filter.

Another strategy used to make narrow bandpasses employs the use of equivalent stacks. The initial design for this method is several stacks of half-wave made of idealized materials. A 3-cavity filter, for instance, is made of two idealized materials A and B: 2A | 2B | 2A
The refractive indices of A and B are varied so that the desired optical profile of the assembly is obtained. The layers are then replaced with symmetrical stacks of a high and low index materials with the same equivalent n and \( \phi \) as the idealized stack. Figure 3 shows the transmittance profile of a 31-layer design narrow bandpass filter using this method (high and low index materials are TiO\(_2\) and SiO\(_2\) respectively).

![Figure 3. (a) A 3D and a (b) topographic plot of the NBF design using variable index materials.](image)

**CONCLUSION**

The designs of both narrow and broad bandpass filters were explored and characterized using the Abeles computational method. In this method, the incident light was reduced into positive and negative going light. The computation of the transmittance of a thin film assembly is reduced to the matrix multiplication of the characteristic matrices of each individual layer.

Several approaches to designing narrow bandpass filters were discussed. The most common approach involved adopting the structure of a Fabry-Perot Interferometer. Adding several of these in series will improve the shape of the NBF. Finally, designing using variable index materials then replacing with equivalent stacks was also considered.

**REFERENCES**


