Jump method for optical thin film design

Lei Li, Qiong-Hua Wang, Da-Hai Li, and Hua-Rong Peng

1School of Electronics and Information Engineering, Sichuan University, Sichuan University, Chengdu 610065, China
2Key Laboratory of Fundamental Synthetic Vision Graphics and Image for National Defense, Sichuan University, Chengdu 610065, China

*qhwang@scu.edu.cn

Abstract: This paper proposes a method called Jump method for optimization of optical thin films. The method is the combination of local search strategy using modified Coordinate-Wise Algorithm and global search strategy using modified Evolutionary Algorithm. Jump method can evolve the designs of optical thin films for good performances. The design of a dielectric beam splitter and an edge filter as examples is carried out and the results indicate that Jump method is a very robust algorithm for optical thin film designs.

©2009 Optical Society of America

OCIS codes: (310.0310) Thin film; (310.4165) Multilayer design.

References and links


1. Introduction

The optical thin film is very important to modern optics. It not only makes great progress in traditional optical precision measurement technology, but also is widely used in high-tech fields such as laser technology, simulation technology, guidance technology, aerospace technology and so on. The problem of optical thin film design can be formulated as an optimization problem based on the use of merit functions [1]. A merit function is a complicated Multi-modal function, when the number of the layers for thin films is more than 8, the peak values of the merit function surge. There are several basic approaches to the design of thin films. They can be divided roughly into three categories: analytical, graphical, and numerical methods [2].

Refinement methods and synthesis methods are two widely used numerical methods for optical thin film designs. The traditional refinement methods [3] such as damped least square, modified gradient, golden section, Hook and Jeeves search, and Simplex method are extremely difficult to search the global minimum because of the large number of local minimum in the merit function [4]. What’s more, the refinement methods heavily depend on and are sensitive to the start point. Unfortunately, good starting designs are not readily available for many modern design problems. On the contrary, synthesis methods such as
Evolutionary Algorithm and needle method [5–7] are much less sensitive to the start point. It can create starting designs randomly, and can evolve the design for good results automatically. More recently, Memetic Algorithm [8] have been applied to optical thin film designs. It can be defined as a class of Evolutionary Algorithm in which local search plays a significant role. It is found to result in faster convergence than in the case when no local searches are employed. The effectiveness of a Memetic Algorithm depends to a large extent on the effectiveness of the local optimization.

In this paper, we propose a new method for optical thin film designs.

2. Theory of Jump method

The proposed approach is called Jump method and it is the combination of refinement method using modified Coordinate-Wise Algorithm and synthesis method using modified Evolutionary Algorithm. On one hand, we use the refinement method as local search strategy to search the local minimum rapidly. On the other hand, we use synthesis method as global search strategy to jump out of the present local minimum for better performance.

2.1 Theory of thin film design

As is shown in Fig. 1, an optical thin film is a multilayer stack consisting of several layers of dielectric materials deposited onto a substrate. The construction parameters include the number of layers (M), the thickness (d), refractive indices (η), and extinction coefficients (k) of the medium, substrate and layer. Generally, the task of thin film design is to find the thicknesses (d_1, ..., d_M) and indices (η_1, ..., η_M) of the thin film. However, it has no advantages to use more than two materials that have low η_l and high η_h refractive indices, respectively. Usually the two materials are given. Therefore, our goal is to search the thicknesses (d_1, ..., d_M) in order to obtain the best performance.

Fig. 1. The structure of the thin film

In this paper, we denote the reflectance as R(η, d, λ_k), where λ_k is the discrete wavelength value. The desired spectral reflectance profiles are fitted by minimizing a suitable merit
function which composes of an appropriate function of $R(\eta, d, \lambda_K)$ defined within the wavelength range. The merit function can be defined in the following equation:

$$F = \sum_{k=1}^{W} \left[ (R(\eta, d, \lambda_K) - R(\lambda_K))^2 \right]^{1/2}.$$  \hspace{1cm} (1)

where $W$ represents the number of wavelength used in calculation, $R(\lambda_K)$ is the target reflectance.

The most general method of calculating $R(\eta, d, \lambda_K)$ is based on a matrix formulation [9]. Therefore, the coating problem can be formulated as a constraint optimization problem.

2.2 Principle of Jump method

Figure 2 shows the basic steps of Jump method.
A solution is randomly generated as the initial solution. Then Jump method enters the main loop. First, the solution enters the Modified Coordinate-Wise Procedure, in which each layer sequentially changes its thickness. Then, when the solution could not be optimized because of the local minimum, it enters the next procedure called Modified Evolutionary Procedure. In this procedure, \( n \) solutions are randomly generated. Combined with the previous solution from Modified Coordinate-Wise Procedure, they make up an evolution population, \( n \) represents population size. Then, the procedure is realized by doing recombination, mutation, and selection. The best one survives. If the solution is better than the previous one from the Modified Coordinate-Wise Procedure, it means the solution escapes from local minimum successfully. Then the output becomes the input of next loop. If not, this procedure will cycle for several times until it turns out to be satisfactory one.

In the following discussion, we use \( d_i \) to represent the \( i \)th thickness of \( M \) layers, and use \( u \) and \( v \) to denote the step sizes of Modified Coordinate-Wise Procedure and Modified Evolutionary Procedure, respectively.

2.2.1 Modified Coordinate-Wise Procedure

In this procedure, our purpose is to search the local minimum rapidly. Therefore, we employ step size \( u \) to change the thickness of each layer as follows:

\[
T' = T \quad (if \ f' < f),
\]

\[
T' = T + 1 \quad (if \ f' > f),
\]

\[
d'_i = d_i + u \quad (if \ T' = 0),
\]

\[
d'_i = d_i - u \quad (if \ T' = 1),
\]

where \( f \) represents the value of the merit function before change, \( f' \) represents the value of the merit function after change. Similarly, \( T \) represents a variable before change, \( T' \) represents the variable after change. Initial value of \( T \) is 0. And \( d'_i \) is the \( i \)th variable of \( d \) after change. We note that if \( T' \) is larger than 1, we change \( i \) into \( i+1 \). Meanwhile, we reset \( T' \) as 0.

In order to find the local minimum effectively, we decrease the step-size vector \( u \) when each layer is self-optimized for a round:

\[
u' = Cu
\]

where \( u' \) is the value of step-size after change, \( C \) is a constant whose value is between 0 and 1 so as to converge. In this paper, \( C \) is set to 0.97.

2.2.2 Modified Evolutionary Procedure

In this procedure, we use modified Evolutionary Algorithm to conduct global search, \( n \) solutions are first generated randomly. The \( n \) solutions combined with the previous solution from Modified Coordinate-Wise Procedure make up a population. Then, the procedure is realized by doing recombination, mutation and selection.

For easy description of the operators, we use \( a = (d^a, v^a) \) to represent a parent, and \( b = (d^b, v^b) \) as another parent. The offspring, \( c = (d^c, v^c) \), is generated by a genetic operation.

Recombination: the two parents of the recombination operator are randomly selected. The child inherits genes from the two parents with a probability \( P_c \). The operator is as follows:

\[
d'_i = d^a_i \quad (with \ the \ probability \ P_c),
\]

\[
d'_i = d^b_i \quad (with \ the \ probability \ 1 - P_c).
\]

In this paper, \( P_c \) is set to 0.4.
Mutation: after recombination a mutation operator is applied. We adapt Schwefel’s proposal [10] to use self-adaptive Gaussian mutation:

\[ v'_i = v''_i \exp \left[ \tau N(0,1) + \tau' N_i(0,1) \right]. \]  
\[ d'_i = d''_i + v'_i N_i(0,1). \]

where \( N(0,1) \) is the standard normal distribution, \( N_i(0,1) \) is a new value with distribution \( N(0,1) \) that must be regenerated for each index \( i \). We set \( \tau \) and \( \tau' \) as follows [6]:

\[ \tau = \left( \frac{2}{\sqrt{n}} \right)^{-1}. \]
\[ \tau' = \left( \frac{2}{\sqrt{n}} \right)^{-1}. \]

Selection: of all the solutions including the parents and children, we evaluate the merit function of each solution. The one with minimum value survives.

For each loop, we compare the solution selected from Modified Evolutionary Procedure with the solution from the Modified Coordinate-Wise Procedure. If the solution selected from Modified Evolutionary Procedure performs better than the solution from the Modified Coordinate-Wise Procedure, the solution will return to the beginning to start a second loop, or else the solution will continue doing Modified Evolutionary Procedure until it turns out to be satisfactory one.

We note that Evolutionary Algorithm is usually used as an approach to search for the global minimum, however, for Jump method, Evolutionary Algorithm is merely used as a method to escape from the local minimum.

### 3. Design examples and results discussion

Jump method can be used to design a wide variety of optical thin films from the ultraviolet to the far infrared wavelength. As design examples, we use it to design a broadband multilayer dielectric film beam splitter and an edge filter in the visible range.

The first design example is to design a beam splitter. The dielectric film is composed of alternating TiO\(_2\) (\( \eta_h = 2.40 \)) and SiO\(_2\) (\( \eta_l = 1.46 \)) layers deposited on a substrate. The transmittance of the dielectric beam splitter can be varied from 0 to 100% by adjusting the individual dielectric layer thickness.

Our target design is the reflectance \( R(\lambda_K) \) specified to 0.5 at 10nm increment between 400nm and 700nm. The incident medium is air (\( \eta_0 = 1 \)) and the substrate is glass (\( \eta_g = 1.5 \)).

The initial number of layers is randomly chosen from 10 to 30. The initial thickness of each layer is uniformly selected from the region from 0 to 200nm.

Table 1 shows the parameters of Jump method used for the simulation of the beam splitter. Table 2 gives some solutions of Jump method for the beam splitter and Fig. 3 shows the wavelength-dependent transmittance of the beam splitter for different number of layers using Jump method. We can see the results are good.

The second design example is to produce an edge filter in visible range. It is also composed of alternating TiO\(_2\) (\( \eta_h = 2.40 \)) and SiO\(_2\) (\( \eta_l = 1.46 \)). Our target design is to transmit blue and green, but reflect red. So the reflectance \( R(\lambda_E) \) is specified to 0 between 400nm and 550nm, and specified to 1 between 550nm and 700nm at 10nm increment. The incident medium is air (\( \eta_0 = 1 \)) and the substrate is glass (\( \eta_g = 1.5 \)).

Table 3 gives the parameters of the edge filter using Jump method. The transmittance curves of the edge filter for Jump method is shown in Fig. 4. It is obvious that the performance of the edge filter using Jump method is very good.

From the examples above, we can make a conclusion that Jump method is very robust in designing thin film. At present, no one technique appears ideal for all design problems, and the proposed method is a useful addition to those available.
Table 1. Parameters of Jump method used for the simulation of the dielectric beam splitter.

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modified Coordinate-Wise Procedure</td>
<td>$C = 0.97$, $u = 2$ nm.</td>
</tr>
<tr>
<td>Modified Evolutionary Procedure</td>
<td>$P_c = 0.4$, $v = 0.05$ nm, $n = 10$.</td>
</tr>
</tbody>
</table>

Table 2. Some parameters of the dielectric beam splitter using Jump method.

<table>
<thead>
<tr>
<th>Number of layers</th>
<th>Total thickness (nm)</th>
<th>Merit function</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>440.8</td>
<td>0.3571</td>
</tr>
<tr>
<td>17</td>
<td>608.1</td>
<td>0.3410</td>
</tr>
<tr>
<td>24</td>
<td>831.9</td>
<td>0.3379</td>
</tr>
</tbody>
</table>

Fig. 3. The wavelength-dependent transmittance of the dielectric beam splitter for different number of layers using Jump method.
Table 3. Some parameters of the edge filter using Jump method.

<table>
<thead>
<tr>
<th>Number of layers</th>
<th>Total thickness (nm)</th>
<th>Merit function</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>1972.7</td>
<td>0.4592</td>
</tr>
</tbody>
</table>

Fig. 4. The transmittance of the edge filter using Jump method.

4. Conclusion

Jump method for optimization of optical thin films is proposed. The method is the combination of local search strategy using modified Coordinate-Wise method and global search strategy using modified Evolutionary Algorithm. Jump method can evolve the designs of optical thin films for good performances. The design of a dielectric beam splitter and an edge filter as examples is carried out and the results indicate that Jump method is a very robust algorithm for optical thin film designs.

Acknowledgments

The work was supported by Program for New Century Excellent Talents in University in China under Grant No. NCET-07-0582.