

Study design edge filter using synthesis needle technique

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Abstract— This study demonstrated design edge filter of long and short- wave pass for mid IR region using needle approach as synthesis method. This approach gave new design stacks of edge filters with optimal specifications as high transmittance, wide stopband, wide passband, sharper edge, and reduced the ripples in passband. Results appear that problem for design (SWP) filter are solved and gave zero transmittance in stopband by using a fewer layers. Also this paper shows design (LWP) with optimal optical performance.

Index Terms— Optical interference filter, Edge filters, Long-wave pass, Short-wave pass, Analytical method, Needle technique, Merit function, Characteristics Matrix.

1 INTRODUCTION

Optical coatings are used to change the spectral intensity distribution or the state of polarization of the electromagnetic radiation incident for satisfying performance specifications, [1,2] they are a key element of nearly every optical device, and have been extensively studied for decades.

These optical coatings which consist of one or more thin films of dielectric or metallic materials, [3,4] are have numerous important applications in many branches of science and technology. [2]

Optical interference filter is the preferred type of optical coatings, which use the phenomenon of interference waves. [5,6] Such filters consists of a number of thin films deposited on substrate, and have the property of being able to reflect range of wavelengths and transmits others. [5,7] Useful application of such coatings is edge filters. [7,8]

Edge filters are the filters in which the primary characteristic is an abrupt change between a region of rejection and a region of transmission, they transmit wavelengths on one side, and stop wavelengths on the other side, of a specified wavelength, known as the edge wavelength, the high transmittance in the passband is usually desired. [7,9,10] Edge filters are divided into two main groups, long-wavepass (LWP) and short-wave pass (SWP). [10]

Edge filters are widely used for various optical purposes, especially in wavelength division multiplexers (WDM), intelligent optical networks, optical fibre communication systems (fibre sensors), and multimedia color projection Display [11,12]. Edge filters are also using to isolate portions of the spectrum in a variety of industrial or life sciences applications including microscopy or fluorescence instrumentation [13,14].

In this paper the use of a needle technique which has been effective method is employed to design optical interference edge filters within the range of wavelength (3-5 μ m), at normal incidence by searching the optimal thicknesses of the layers, where materials of layer coating assumed to be fixed in design (LWP) and (SWP).

2 THEORETICAL BACKGROUND

The performance of interference filters may be altered by changing the characteristic of the component films i.e, refractive index of layers and optical thickness [6,7,15].

Many different approaches for design interference optical filters which they are often required to reach the solutions of different types of problems, these approaches can be roughly divided into [1,16,17]:

- 1- Graphical vector methods
- 2- Analytical synthesis methods
- 3- Numerical design methods

Numerical method are the most widely used techniques because they are particularly powerful for the solution of complicated spectral problems that can not solve with others methods, and can be applied to the design of coatings with very complicated specifications requiring a large number of layers for their solution [2,15]. Refinement methods and synthesis methods are two widely used categories of numerical methods for optical thin film designs. [18]

Refinement requires an initial design as a starting solution, and the challenge consists in improving this solution [17,19]. In complex cases in which one cannot guess a possible starting solution, refinement methods are dramatically inefficient. It is therefore of great interest to be able to synthesize a solution even if a further treatment is necessary [17]. Contrary to refinement methods, synthesis methods, generate their own starting designs automatically. One of the most commonly used techniques is the needle method [17,20,21].

2.1 needle optimization technique

The optimization problem can be described as the search for construction parameters of the system that lead to the best satisfaction of the desired optical performance [22].

The problem of optical coating design was first formulated as an optimization problem by Baumeister in 1958, this approach is now the most widely used design method for optical filters [23,24].

The performance of the design during the optimization procedure is based on the use of the merit function that measures the discrepancy between the target and solution[1,22,25].

Needle synthesis is the most commonly and efficient used optimization design technique that was born in the late of 1980 by two russian scientist,sh.a.furman Alexander V.Tichonravovv. In general, needle technique consist of sequence of insertions of new layers in multilayer structure, each followed by a sequence of optimizations to their thickness [23]. The used merit function form is which proposed by Dobrowolski which is defined as [24,26] :

$$MF = \left[\frac{1}{m} \sum_{i=1}^m \left[\frac{Q_i^r - Q_i}{\delta Q_i} \right]^k \right]^{\frac{1}{k}}$$

The challenge consists in improving this solution by minimizing merit function which has be minimized by modifying of several design parameters like the thickness and refractive indices of the individual layers [22,27] .

2.2 Multilayer matrix calculations

This study depended calculations Characteristics Matrix to determine the spectral transmittance profile for multilayer structures on a substrate.

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 [6,28]:

$$\begin{bmatrix} C \\ B \end{bmatrix} = \left(\prod_{r=1}^q \begin{bmatrix} \cos \delta_r & (i \sin \delta_r) / n_r \\ i n_r \sin \delta_r & \cos \delta_r \end{bmatrix} \right)$$

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

$$\delta_r = 2\pi n_r dr / \lambda$$

n_r, dr 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 .

The expression for transmittance of the multilayer system which is defined as the ratio of the output intensity from thin film assembly to input intensity, is given as follow :

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

$\text{Re}(n_s)$ represents to real part of refractive index of substrate.

3 DESIGNS AND DISCUSSION

In this work, we apply approach depends on the needle optimization as synthesis method and characteristic matrix to design edge filters of short-wave pass and long-wave pass, And compared these new designs computed by needle technique with the analytical (classical) designs, for mid infrared region (MWIR) (3-5 μm) with utilize a silicon as substrate (Si), and adopted (ZnSe) as a high refractive index material and (MgF₂) as a low refractive index material .

3.1 analytical method

There are two basic multilayer designs that are currently used for Edge filters. One design has the pass-band on the high wavelength side of the stop-band, the other on the low wavelength side. The designs are the following :

[0.5H (LH)^{s-1} L 0.5H] long-wave pass stack

and

[0.5L (HL)^{s-1} H 0.5L] short-wave pass stack

Optical performance of such stacks is characterized by sever ripples in passband due to the mismatching between the coating materials and the surrounding medium, and limited stop-band range depending on the ratio of the indices of the two materials that used in the construction of the multilayer coating, a high ratio of refractive indices gives the widest rejection zone [29,30].

However the performance of the edge filters could be very much improved if the ripples could be reduced (or eliminated) that by the use of powerful computers in a process of refinement or even complete synthesis [6,14]. Needle synthesis is one of the most efficient design technique which we used to design edge filters in this work.

3.2 Needle technique

a. Long-wave pass

In this section long-wave pass filters are designed by needle synthesis as shown in figures (1,2,3), where we got higher transmission reach to (100%) ,relatively severe edge, wide-width of stopband , and the ripples are reduced by using a fewer number of layers and with different slight thicknesses, as shown in the figure (1), also figure (1) appear new construction of needle design using 22 coating layers .

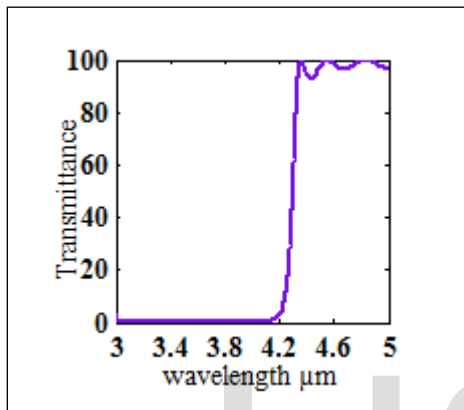


Figure (1). Optical performance of (LWP) designed by needle technique With using 22 layers.

0.79889335H 0.57606858L 0.86118392H 0.9597555L 0.97323668H
 0.91710108L 0.84227424H 0.80261214L 0.83482939H 0.91072686L
 0.9446953H 0.94047966L 0.89537526H 0.83298594L 0.80955036H
 0.84812868L 0.91987276H 0.96976878L 0.96615272H 0.82392486L
 0.6417867H 0.73732986L

Figure (2) shows other new design stack of needle technique constructed long-wave pass filter with also 22 coating layers, this new design have longer range of transmission from 3.8 μm to 5 μm with more decrease of ripples, and relative steepness edge.

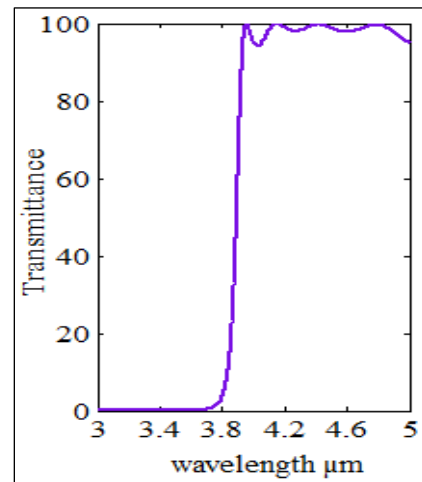


Figure (2). Optical performance of (LWP) designed by needle technique for 22 layers.

0.470528262H 0.988016175L 1.055397112H 1.00867995L 0.968102362H
 0.96185655L 0.984542575H 1.0080831L 1.012935775H 1.00165575L
 0.99069085H 0.988775175L 0.996492575H 1.007398275L 1.006336388H
 0.9882732L 0.96851165H 0.9719685L 1.004809775H 1041991425L
 0.9767213H 0.53351145L

When needle technique increased the layers we got optimal long-wave pass filter by using 24 layers, figure (3) demonstrates such optimum design.

As it is shown we got optimum (LWP) with long range of transmittance, zero transmittance in stopband, high steepness edge, and ripples reduced (highly suppressed) .

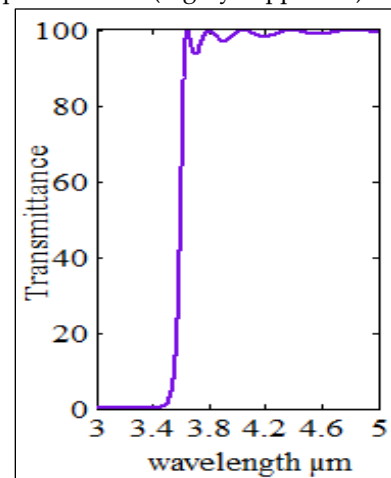


Figure (3). Optical performance of (LWP) designed by needle technique for 24 layers.

2.038441125L 0.7359766H 0.332785L 0.912606562H 0.9223506L
 0.91425865H 0.911829825L 0.918196175H 0.925129575L 0.925805338H
 0.92445855L 0.924311588H 0.924453375L 0.92355575H 0.92359605L
 0.925219788H 0.9217986L 0.914512588H 0.9131184L 0.917864562H
 0.90817455L 0.850030388H 0.742038075L 2.008517162H

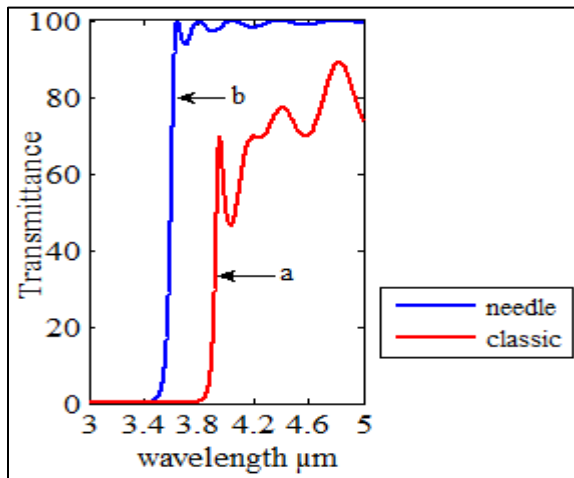


Figure (4). Comparison between (LWP) designed by analytical method and needle technique

Figure (4) displays (LWP) designed by using analytical construction which is for such case $[H/2 (LH)^{10} L H/2]$ (curve a) and (LWP) designed by needle technique (curve b) using 24 layers.

Needle technique design have transmittance value higher than classical design, the range of transmittance is longer in case of needle design, and the ripples are eliminated in pass-band, while there is severe ripples in pass band of classical design. thus the problem of mismatching coating materials with substrate and incidence medium that it is caused ripples in passband was solved with needle technique.

b. Short-wave pass filter

Short-wave pass filters are designed using needle synthesis method and we overcame many of the design problems. such new design stacks characterized by high transmission reach to (100%), relatively steep edge, wider pass band width, and ripples reduced (highly suppressed) by using fewer layers with different thickness as shown in figures (5,6).

Where figure (5) shows the optimization design of short-wave pass filter with needle technique by using 15 coating layers, the effect of increase layer coating appears in figure (6) when needle technique increased the layers we got optimum short-wave pass filter by using 18 layers with decreased ripples in transmittance region. Figures (5,6) appears new construction stack design a raised by needle technique for short-wave pass filter.

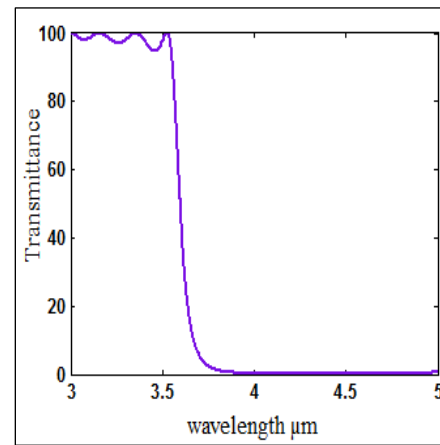


Figure (5). Optical performance of (SWP) designed by needle technique for 15 coating layers

1.39535131H 1.03960368L 0.99669453H 1.07454804L 1.14321587H
 1.08133488L 1.01214349H 1.01544678L 1.15322736H 1.15322736L
 1.0428287H 0.95052192L 1.15763952H 1.242L 0.21443558H

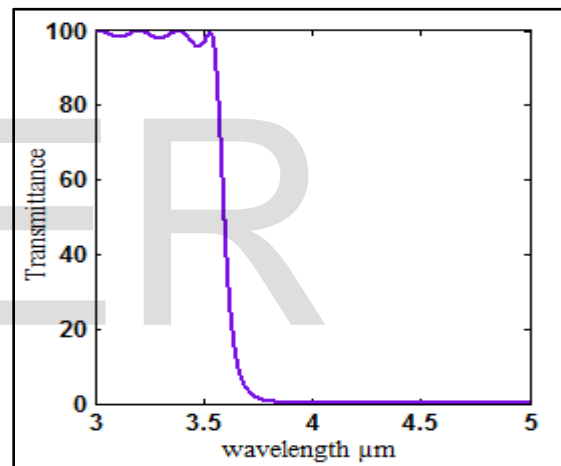
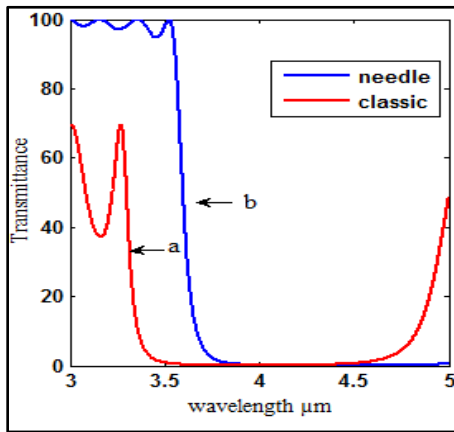


Figure (6). Optical performance of (SWP) designed by needle synthesis method for 18 layers.

0.413216L 1.16532H 1.10132832L 1.06964689H 1.06856574L 1.07332271H
 1.07118912L 1.06333968H 1.05762786L 1.05899705H 1.0660707L
 1.07349718H 1.07335848L 1.07452249H 1.0824582L 1.1026265H
 1.16916498L 0.42666758H

Figure (7) displays (SWP) designed by classical analytical method with using analytical construction which is for such case $[L/2 (HL)^6 H L/2]$ (curve a) and (SWP) designed by needle technique (curve b) using 15 layers. Differences between their spectral performance are evident.



Figure(7). Comparison between Short-wave pass designed by analytical method and needle technique

Transmittance results of needle technique design higher than classical method and differs by (30%), needle design minimised the ripples in pass band (almost eliminated), while there is some ripples in pass band of classical design .

The transmittance range of needle technique design increased, and as it is shown in the figure (7) transmittance region width of needle longer than classical design by about (2.5 μm) . As it's clear in the needle technique design that the problem of stop-band is solved and its being zero transmission within the range (4.6-5 μm) which it is not zero transmission in case of classical design, where rejection region of needle design is between 3.8 and 5, and in classical design it's between 3.8 μm and 4.6 μm as shown in figure (7).

4 CONCLUSIONS

This study has presented the needle technique as a powerful synthesis approach to design new stacks for edge filter of long and short- wave pass by using a fewer number of layers. Also the coating materials system ZnSe/MgF₂ offers great promise for use in design two types of edge filter in the (3-5 μm) wavelength range .

Comparing with the analytical method the needle technique gives higher transmittance reaches to (100%) , wide stopband , wide passband and the ripples are reduced in passband by using fewer layers with controlling their thickness .

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