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New Construction Stacks for Optimization Designs of Edge Filter

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Abstract: *This study presents new construction design stacks for optimal edge filters of long and short- wave pass using a needle technique as synthesis method. We investigated construction stacks have proper number of layers with controlling the thickness of each layer. In visible-near IR region (0.3-0.9µm), here we intend to investigate solutions for many practical problems. Results appears procedure highest transmittance reach to (100%) with maintained the steepness of edge. Also results demonstrate that our approach is powerful technique enable to offered new design construction with advanced performance where no ripples in passband for wider range of wavelengths.*
Keywords: *Designs of edge filter, modelling of edge filters, optimization interference filters*

I. Introduction

Interference filters are devices that selectively transmits or reflects electromagnetic radiation of desired region. These filters are not only make great progress in traditional optical precision measurement technology, also are widely used in high-tech fields such as laser technology, simulation technology, guidance technology, aerospace technology and so on [1,2]. Interference filters can include some tens even hundreds of dielectric layers of materials with differences in refractive indices [3,4,5,6]. These filters use the waves interference phenomenon, Such filters have the property of being able to reflect some wavelength and transmit others to enable effects such as edge filters, band pass, beam splitter and others [7,8,9].

Edge filters are produced with using of alternating high and low refractive index materials which characterised by an abrupt change between a region of rejection (stopband), and a region of transmission (passband). They transmit wavelengths on one side, and reflect wavelengths on the other side of a specified wavelength, known as the edge wavelength, high transmittance in the passband is usually desired [9,10,11] .

Edge filters are divided into two main types, long-wave pass (LWP) and short-wave pass (SWP). These filters are widely used for various optical purposes, especially in wavelength division multiplexers (WDM), optical fibre communication systems, and multimedia color projection display [12,13,14].

There is many different approaches for design interference optical filters, these approaches can be roughly divided into, Graphical method, Analytical method, Numerical method [15,16,17,18]. In the design of a multilayer optical filter, it is necessary to find a construction which will give a performance specified in advance this procedure is much more difficult than calculation of the properties of thin film layers, there is no graphical and analytical solution to this problem [19].

Numerical method are the most widely used techniques 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 [16,20]. Refinement methods and synthesis methods are two widely used numerical methods for optical thin film designs. [2,20]. The traditional refinement methods heavily depend on the initial design as a starting solution. Unfortunately, good starting designs are not readily available for many modern design problems. Contrary to refinement methods, synthesis methods generate their own starting designs automatically [21,22].

One of the most commonly used techniques is the needle technique. Needle synthesis is a powerful method for producing designs with complex performance. In this paper we apply technique depends on the needle optimization as a synthesis method and characteristics matrix to design optimal edge filters of long-wave pass and short-wave pass for visible-near IR region (0.3-0.9 µm) .

II. Edge Filters And The Conventional Design (Analytical Design)

The basic type of analytical design interference edge filter is the quarter-wave stack with eight-wave layers at each end [23,24]. One design has the passband on the high wavelength side of the stopband,the other on the low wavelengths side. The construction design of edge filter as the following [11,25]:

no $[0.5H\ (LH)^S\ L\ 0.5H]\ n_S$ long-wave pass stack
and
no $[0.5L\ (HL)^S\ H\ 0.5L]\ n_S$ short-wave pass stack

Where H and L are quarter-wave optical thickness of high index layer and low index layer respectively, the double–layer combination (HL) stack between massive substrate (n_S) and air (n_O) is repeated S times, S also called order of periodicity. In analytical approach the ripples appear in passband because of the mismatching between the coating materials and the surrounding medium [26,27]. These ripples are severe and the performance of the filter design would be very quite difficult task.

III. Theory Of Needle Synthesis Method

The problem of optical coating design can be formulated as an optimization problem [28,29]. The improving performance of the design during the optimization procedure is achieved by minimizing merit function that measures the discrepancy between the target and solution [1,30]. Merit function has be minimized by modifying of several design parameters like the thickness and refractive indices of the individual layers [5]. The most important merit function (MF) form is that proposed by Dobrowolski which is defined as [28,31]:

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

Optimization technique consists of three separate components[32]:

1- List of design goals or targets.
2- Set of variables.
3- An optimization algorithm. The optimization algorithm is used to adjust any given variables to make the system performance matched the design goals

Needle synthesis is the most powerful optimization technique that was submitted in 1980 [28,33]. The principal feature of needle optimization technique is that the choice of starting design is not problem. The essence of needle technique is that algorithm identifies the convenient places to insert new layers that will improve the merit function. The algorithm will also identify which layer material, from a pre-selected group materials (specified by the user) will provide the greatest improvement [28]. Once the process has been initiated and the needle layer has been inserted into the existing design, the thicknesses of the resulting assembly of layers is refined to further decrease the value of the merit function by adjusting the thickness of layers in the stack. This process may be successively iterated without intervention until the introduction of needle layer no longer affects decrease in the merit function [34]. A general schematic of needle optimization synthesis procedure is shown in Fig. (1)

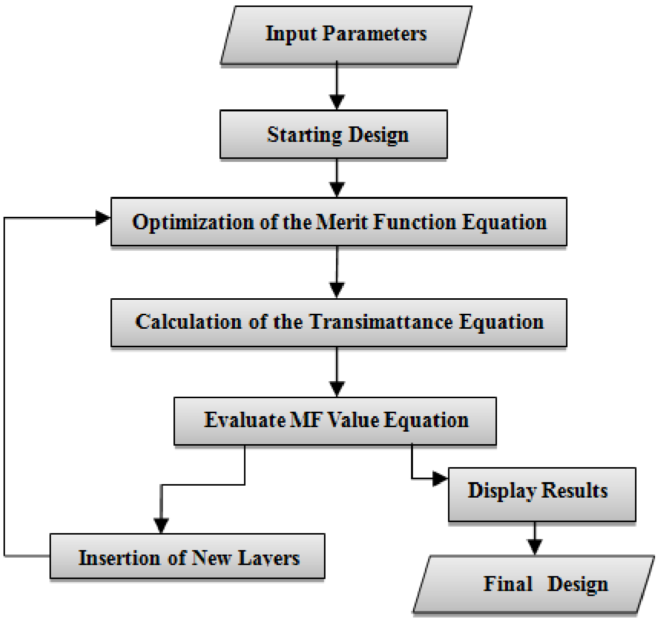

Figure 1: General scheme of the synthesis procedure based on the needle optimization technique [28]

IV. Optimization Design And Results Discussion

In this section, we designed edge filters of long-and short-pass wave by numerical optimization method (needle technique), and studied their optical performance for visible-near IR region (0.3-0.9 µm). The dielectric edge filter is composed of alternating ZrO_2 (n_H =2.05) and MgF_2 (n_L= 1.38) layers deposited on a glass (n_S=1.52).

Figures (2,3,4) present the optical performance of short-wave pass filter designed by needle technique, where high transmittance reaches to (100%) within wavelength (0.3-0.7 µm) and zero transmittance in stopband within range of wavelength (0.7- 0.9µm) are gotten. Fig. (2) shows new design construction stack of short-wave pass filter using 24 coating layers offers improved optical performance of (SWP).

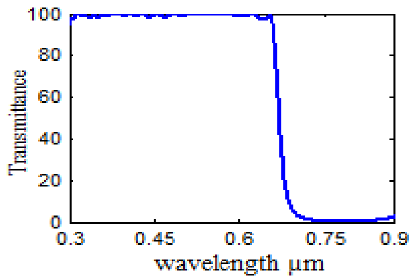

Figure 2: Optical performance of (SWP) designed by needle technique using 24 layers with construction design stack [0.54745152L 1.0709067H 1.06254848L 1.0425917H 1.0506768L 1.0314616H 1.0186608L 1.011497333H 1.0159744L 1.022091733H 1.01885952L 100942H 1.0071939L 1.025975804H 1.03568448L 1.04755467H 1.0717337L 1.120535467H 1.24147744L 0.229272H 0.185656L 1.424088H 0.15302176L 0.222373067H].

The coating layers are increased to 25 to get optimal short-wave pass filter as shown in Fig. (3). This design has new construction due to use additional layer and smaller total thickness, there is benefit from the increase of the number of the layers via minimizing the total thickness, and this status could assist to overcome the manufacturing problems.

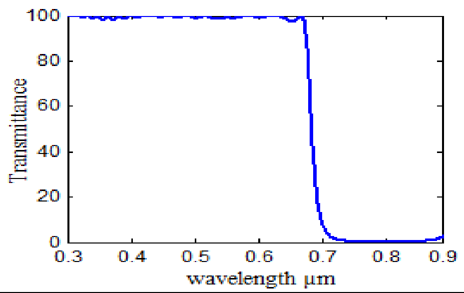

Figure 3: Optical performance of (SWP) designed by needle technique using 25 layers with construction design stack [0.52225088L 1.0587949333H 1.06876032L 1.0671917333H 1.05510752L 1.049851667H 1.0365824L 1.0264213333H 1.03056928L 1.0406456H 1.04306656L 1.0355397333H 1.02719104L 1.0300512H 1.0422128L 1.0544762667H 1.0609072L 1.0617688H 1.0386432L 0.15698087H 0.0935088L 0.9654461333H 0.18135776L 0.13366H 0.91620224L].

We have managed to keep the optimum spectral performance in design of (SWP) as shown in Fig. (4). Where transmittance reach to (100%) with high eliminated ripples, wide range of transmision equal to 400 nm, zero transmision in stopband with maintained the steepness of edge . This optimized performance obtained by using 30 coating layers with thinner thickness of each layer, the data of this design viewed in Table (1).

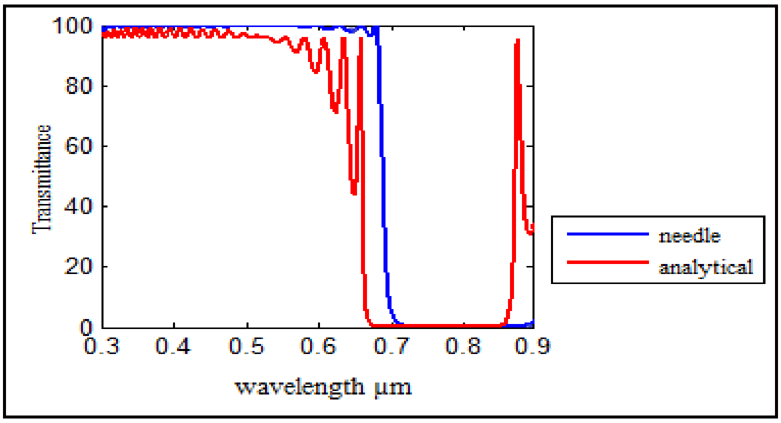

Figure 4: Comparison between (SWP) designed by needle (□ new technique) and analytical (— classic method)

Also Figure (4) displays the comparison designed (SWP) with 31 coating layers by classical (analytical). As is evident in needle technique design the transmittance is the highest through longer range of wavelengths. The passband free of ripples, while there are high severe ripples in analytical design. Within this concerned range of wavelengths the problem of stopband solved and got zero transmission. It must be pointed that the increase the number of layers assisted to get the optimal design when using needle technique but it is impossible to achieve when using analytical method, because the analytical design leads at the same time to increase the ripples in the passband with reduce the transmittance and this is not desirable [2,25]. While needle technique could to give design has good performance in passband, stopband with maintained of the steepness of edge, as shown in Fig. (4).

Table 1: Refractive index and thickness of coating materials for (SWP) designed by (−) needle technique and (−) analytical method within visible-near IR region

Layer number	Material Coating	Index	Thickness for (□) needle design (d)	Thickness for (□) analytical design (d)
n_S	Glass	1.52	Massive	Massive
1	MgF_2	1.38	72.581	67.934
2	ZrO_2	2.05	98.825	91.463
3	MgF_2	1.38	147.827	135.869
4	ZrO_2	2.05	98.859	91.463
5	MgF_2	1.38	145.178	135.869
6	ZrO_2	2.05	96.751	91.463
7	MgF_2	1.38	142.209	135.869
8	ZrO_2	2.05	94.913	91.463
9	MgF_2	1.38	140.929	135.869
10	ZrO_2	2.05	95.354	91.463
11	MgF_2	1.38	141.836	135.869
12	ZrO_2	2.05	94.953	91.463
13	MgF_2	1.38	140.136	135.869
14	ZrO_2	2.05	94.37	91.463
15	MgF_2	1.38	141.12	135.869
16	ZrO_2	2.05	95.455	91.463
17	MgF_2	1.38	141.532	135.869
18	ZrO_2	2.05	94.807	91.463
19	MgF_2	1.38	140.949	135.869
20	ZrO_2	2.05	95.725	91.463
21	MgF_2	1.38	143.779	135.869
22	ZrO_2	2.05	97.627	91.463
23	MgF_2	1.38	145.95	135.869
24	ZrO_2	2.05	99.15	91.463
25	MgF_2	1.38	140.01	135.869
26	ZrO_2	2.05	13.661	91.463
27	MgF_2	1.38	12.223	135.869
28	ZrO_2	2.05	92.389	91.463
29	MgF_2	1.38	20.997	135.869
30	ZrO_2	2.05	12.956	91.463
31	MgF_2	1.38	-	67.934
-	-	-	$\sum d$ =3093.05 nm	$\sum d$ =3409.999 nm
Air	-	1	Massive	Massive

The optimal design of (LWP) shown in figure (5). Which it provided a good performance in the passband that represented by the wide range of wavelength between (0.5-0.9µm) with reducing ripples, zero transmission in stopband between (0.4-0.5µm). The overall thickness of the such design involving 32 layers is 2282.866nm.

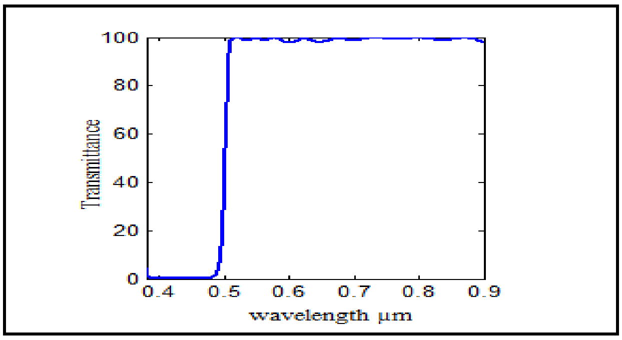

Figure 5: Optical performance of (LWP) designed by needle technique with construction design stack [0.342140444H 1.101252267L 0.96688933H 0.890731733L 0.765369778H 0.631831467L 2.668061333H 0.482460267L 0.779546667H 0.97938667L 0.978642667H 0.88307733L 0.835124444H 0.5807776L 0.99688311H 0.794462933L 1.056287556H 1.040912533L 0.921260889H 0.911082133L 0.973431111H 1.0450096L 0.959910222H 0.837518933L 1.105852H 0.985037867L 0.823425778H 0.9482256L 0.974032444H 0.86596533L 0.516399556H 3.86548267L].

The number of layers is increased to get high performance design . This increasing leads to design (LWP) with optimal specifications design at 35 layers. With total thickness equal to 1825.706 nm less than the total thickness of the previous design as appears in Fig. (6). Which it includes a good optical performance in the passband within range more than 400 nm, highly reduced ripples, zero transmission in stopband. data of this design viewed in Table (2).

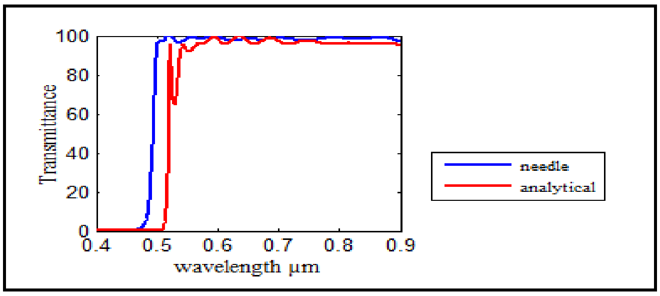

Figure 6: Comparison between (LWP) designed by needle (— new technique) and analytical (— classic method)

Also this Figure demonstrates the comparison of optical performance design by needle technique and analytical method. It s clear from this comparsion that needle technique offered new construction with advanced performance where no ripples in passband for wider range of wavelengths.

Table 2: Refractive index and thickness of coating materials for (LWP) designed by (−) needle technique and (−) analytical method within visible-near IR region

Layer number	Material Coating	Index	Thickness for (□) needle design (d)	Thickness for (□) analytical design (d)
n_S	glass	1.52	Massive	Massive
1	ZrO_2	2.05	22.364	27.439
2	MgF_2	1.38	84.158	81.521
3	ZrO_2	2.05	49.896	54.878
4	MgF_2	1.38	63.518	81.521
5	ZrO_2	2.05	38.33	54.878
6	MgF_2	1.38	59.539	81.521
7	ZrO_2	2.05	33.341	54.878
8	MgF_2	1.38	55.392	81.521
9	ZrO_2	2.05	46.499	54.878

10	**MgF_2**	**1.38**	**70.224**	**81.521**
11	**ZrO_2**	**2.05**	**48.12**	**54.878**
12	**MgF_2**	**1.38**	**60.941**	**81.521**
13	**ZrO_2**	**2.05**	**26.054**	**54.878**
14	**MgF_2**	**1.38**	**10.943**	**81.521**
15	**ZrO2**	**2.05**	**39.425**	**54.878**
16	**MgF_2**	**1.38**	**68.397**	**81.521**
17	**ZrO_2**	**2.05**	**49.641**	**54.878**
18	**MgF_2**	**1.38**	**72.753**	**81.521**
19	**ZrO_2**	**2.05**	**29.043**	**54.878**
20	**MgF_2**	**1.38**	**10.978**	**81.521**
21	**ZrO_2**	**2.05**	**33.259**	**54.878**
22	**MgF_2**	**1.38**	**66.626**	**81.521**
23	**ZrO_2**	**2.05**	**50.972**	**54.878**
24	**MgF_2**	**1.38**	**78.06**	**81.521**
25	**ZrO_2**	**2.05**	**53.979**	**54.878**
26	**MgF_2**	**1.38**	**73.597**	**81.521**
27	**ZrO_2**	**2.05**	**53.814**	**54.878**
28	**MgF_2**	**1.38**	**77.931**	**81.521**
29	**ZrO_2**	**2.05**	**51.769**	**54.878**
30	**MgF_2**	**1.38**	**75.776**	**81.521**
31	**ZrO_2**	**2.05**	**50.865**	**54.878**
32	**MgF_2**	**1.38**	**74.838**	**81.521**
33	**ZrO_2**	**2.05**	**49.163**	**54.878**
34	**MgF_2**	**1.38**	**67.803**	**81.521**
35	**ZrO_2**	**2.05**	**27.698**	**27.439**
-	-	-	**$\sum d$ =1825.706 nm**	**$\sum d$ = 2318.783 nm**
Air	**-**	**1**	**Massive**	**Massive**

At the same number of coating layers (35 layers) This new construction design offered successfully better optical performance as shown in Fig. (7).

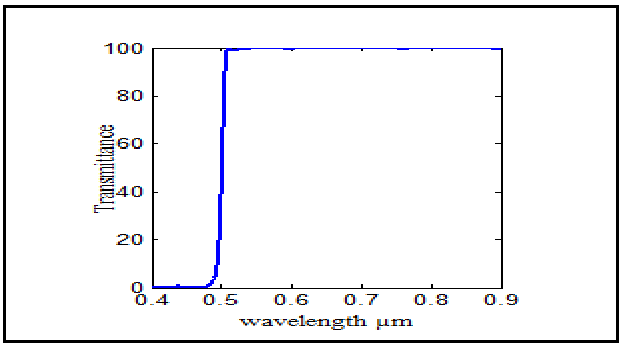

Figure 7: Optical performance of (LWP) designed by needle technique using 35 layers with construction design stack [1.698994667L 0.901471556H 0.76188266L 0.85960889H 0.95483733L 0.9607322H 0.80408L 0.519315111H 2.657794133L 0.51918755H 0.8554528L 0.97532622H 0.9612896L 0.93029911H 0.930794667L 0.912423111H 1.169369067L 0.834887556H 0.95629706L 1.036680444H 0.9687968L 0.949487111H 0.924477333L 0.88696668H 1.369462933L 0.483708889H 1.38588L 0.55897778H 0.916491733L 0.933597333H 0.917583467L 0.913024444H 0.92458667L 0.58245511H 0.620251733L].

V. Conclusions

This study has put up mathematical algorithm depends on synthesis needle technique which is submitted as approach to design new stacks for edge filters of long and short- wave pass. From above results it's obvious that we overcame the problems of designing edge filters of long-wave pass and short-wave pass and obtain designs with optimal optical performance in the passband and stopband by use specific coating materials in design to keep not use materials are not available in nature or hazardous to health.

Where we enable to reduce ripples in passband so the problems of mismatching between the coating materials and the surrounding media which it causes the ripples are solved. And got steep edge with keep the best performance in passband and stopband . Also we would to get stopband along shorter range of wavelengths than the corresponding analytical design where as it is known the width of stopband is assigned by the ratio n_H/n_L , hence needle technique assists us to be able to specified the stopband width.

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