Designing of a linear variable optical filter with narrow bandpass

Amir Etebari*

*(Department of Electrical Engineering, Ahar Branch, Islamic Azad University, Ahar, Iran.)

ABSTRACT

In this study, simulation and fabrication of a linear variable optical filter with Fabry-Perot structure is proposed. This filter is designed in order to detect some spectral lines in the range of 610nm to 680nm that Full Width Half Maximum (FWHM) is less than 4nm. We use two transparent materials for example TiO_2 and SiO_2, respectively as high and low refractive index substances. In visible range, the refractive index of TiO_2 is about 2.5 and the refractive index of SiO_2 is about 1.46. Transfer Matrix Method (TMM) and TFCalc software can be used to calculate thickness of each dielectric layer and transmission factor of an optical filter.

A blocking filter is required in line with the bandpass filter to reflect all wavelengths of visible spectrum except the range of 610nm to 680nm. The thickness values of the blocking filter layers can be obtained via an optimization procedure in TFCalc software.

Keywords **– Transfer Matrix Method, Linear Variable Optical Filter, Blocking Filter**

I. INTRODUCTION

Micro-cavity filter or all dielectric Fabry – Perot filter is a special class of interference filters. According to figure 1, if optical thickness of a cavity layer that surrounded by two symmetric Distributed Bragg Reflectors (DBR) is integer multiples of λ / 2 then this structure is named a micro-cavity filter.

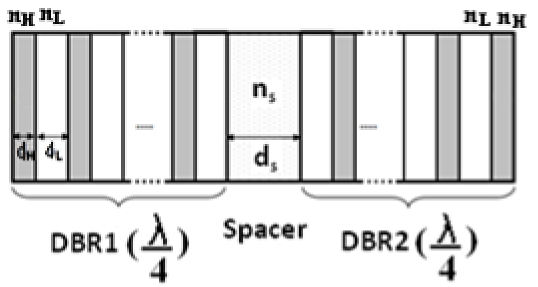

Fig. 1. Microcavity Structure

Distributed Bragg Reflector (DBR) or dielectric mirror is periodic repetition of two layers with different refractive indexes (n_H, n_L) and different thicknesses (d_H,d_L) as $n_H \times d_H = n_L \times d_L = \lambda / 4$ is established for each layer. Relationship $n_S \times d_S = K \times (\lambda / 2)$ is also used for the cavity layer [1]. K is an integer and λ is centric wavelength of an optical bandpass filter.

Micro-cavity filters are used as steady filters [2], adjustable filters [3],[4] and chemical detectors [5]. Dielectric optical filters with Fabry – Perot structures are used in telecommunication, lasers and spectrometers in order to control and measure the exact wavelength range of visible and non-visible spectrum [6],[7],[8]. In a spectrometer, the optical filter with Fabry – Perot style is used to detect the wavelengths that are very close together [10]. The linear variable optical filter (LVOF) is a multi-layer fabry-perot filter that the shape of its cavity is conical. The feasibility study of a linear variable optical filter has been carried out in a wide range (400 nm to 1000 nm) and a narrow range (from 610 nm to 680 nm and from 722 nm to 880 nm) [9],[11],[15].

II. DESCRIPTIONS AND DETAILS

In this section, we describe the proposed structure in the following steps. How to design and how to fabricate a bandpass filter and a blocking filter and results of transmission simulation employing TFCalc software will be illustrated. The bandpass filter with Fabry-Perot structure is designed in order to detect some spectral lines in the range of 610nm to 680nm that Full Width Half Maximum (FWHM) is less than 4nm. We use TiO_2 and SiO_2, respectively as high and low refractive index substances that are transparent in the visible range. Refractive index of SiO_2 is about 1.46 and refractive index of TiO_2 is about 2.5. A blocking filter is required in line with the bandpass filter to prevent all wavelengths of the visible spectrum except the desired range (610 nm to 680 nm). In figure 2 the physical location of the bandpass filter and the blocking filter is shown.

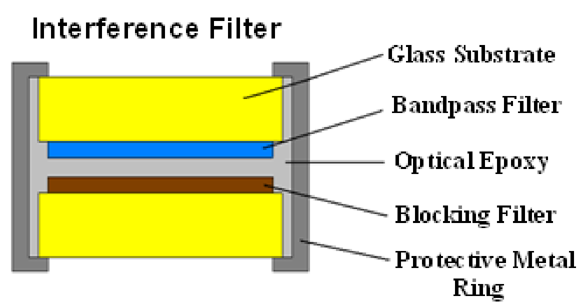

Fig. 2. Components of an interference filter

A. HOW TO DESIGN A BANDPASS FILTER

For designing of a bandpass optical filter we use one dimension structure

(HLHLHLHXHLHLHLH) according to figure 3. Multi-layer (HLHLHLH) and middle layer (X) respectively represent the stack and the cavity of the bandpass filter. L and X are representative of SiO_2 and H is representative of TiO_2. The reference wavelength can be selected 680 nm. Optical thickness of each layer (H and L) is equal to one-quarter of the reference wavelength. The physical thickness of a layer multiplied by the refractive index of the same layer is defined as the optical thickness. For passing the reference wavelength (680nm) through the bandpass filter, the optical thickness of the middle layer (X) must be equal to even multiple of one-quarter of the reference wavelength (680nm).

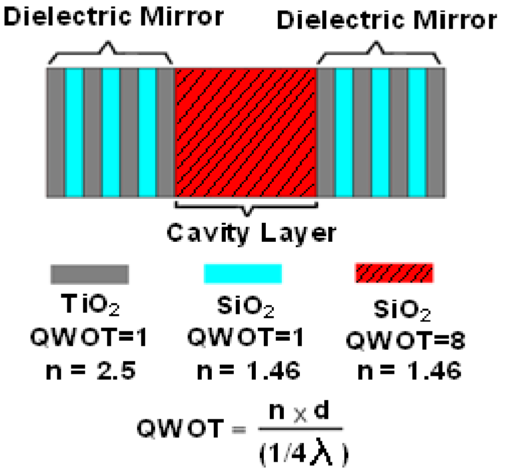

Fig. 3. One dimension structure of a cavity and stacks

According to Table 1, for transmitting all wavelengths in the range of 610nm to 680nm, the thickness of the cavity must be changed from 931.5nm to 801.06nm.

With reference to Table 1, we can perceive that when the thickness of the cavity changes from 931.5nm to 801.06nm then the band width (FWHM) increases from 2.786nm to 3.634nm.

For example, in Figure 4, spectrum of a bandpass filter is shown with central wavelength of 610nm and in the range of 595nm to 625nm. In Figure 5, spectrum of the same filter is shown in the wider range of 400nm to 700nm by using TFCalc software.

Table 1. center wave length dependent to cavity thickness

Center-Wavelength (nm)	FWHM (nm)	Cavity Thickness (nm)
680	2.786	931.5
670	2.772	913.2
660	2.779	894.9
650	2.814	876.5
640	2.914	858.03
630	3.071	839.36
620	3.300	820.39
610	3.634	801.06

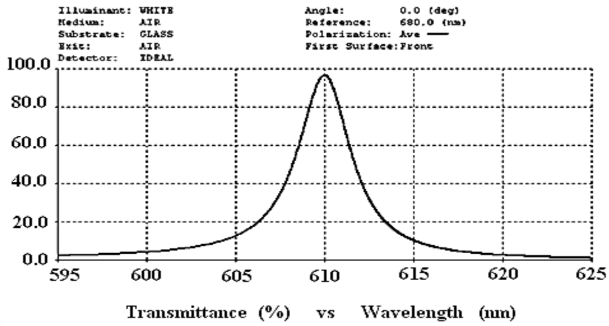

Fig. 4. Spectrum of a bandpass filter with center wave length of 610 nm

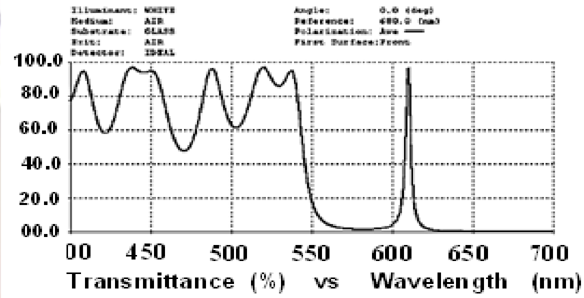

Fig. 5. Spectrum of a bandpass filter with center-wave length of 610 nm and undesired wavelengths

B. HOW TO DESIGN A BLOCKING FILTER

In order to design a blocking filter, we use a structure in the form of HL^20. The transmission range of this blocking filter is shown in figure 6. This filter blocks all visible wavelengths except between 610nm and 680nm. By using TFCalc software, we can obtain an optimal bandwidth in the method of gradient. Before optimization, the thickness of all layers of both H and L is assumed to be equal to one quarter of reference wavelength. After optimizing in the method of gradient, the thickness of all layers changes to get the desirable spectrum in figure 7.

According to figure 7, the outside wavelengths of the passband are sharply blocked by using the optimized filter. The transmission of the prevented band in optimized filter is less than 5%.

For example, the thickness of some layers of the optimized filter is given in Table 2.

Table 2. the thickness of some layers of the optimized filter

Layer number	Material	QWOT	Thickness(nm)
1	TiO_2	0.3583	28.96
2	SiO_2	0.9516	131.69
3	TiO_2	1.6949	136.98
4	SiO_2	0.7213	99.82
5	TiO_2	0.7130	57.62
36	SiO_2	1.5574	215.52
37	TiO_2	0.5066	40.94
38	SiO_2	1.6627	230.10
39	TiO_2	0.6016	48.62
40	SiO_2	1.0208	141.27

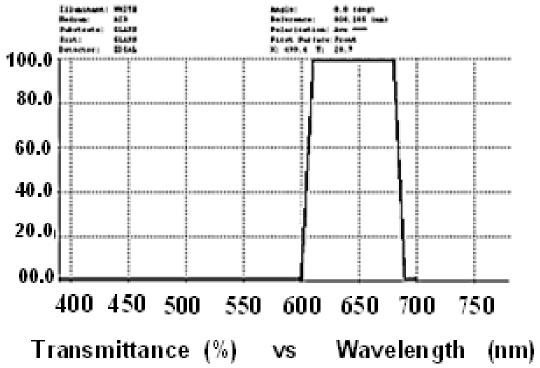

Fig. 6. Characterizing of bandpass spectrum by TFCalc software

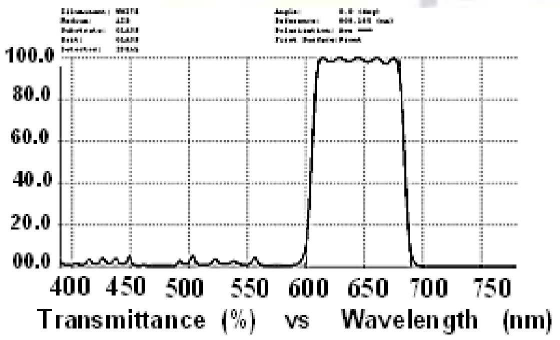

Fig. 7. Bandpass spectrum of structure (HL)^20 after optimization process

C. HOW TO FABRICATE AN OPTICAL FILTER

In the range of 610 nm to 680 nm, the linear variable optical filter method can be used to transmit beams with a band width of less than 4 nm. According to figure 8, the thickness of the cavity layer (X) horizontally changes from 6.88 QWOT to 8.00 QWOT. One quarter of the optical thickness is named 1 QWOT.

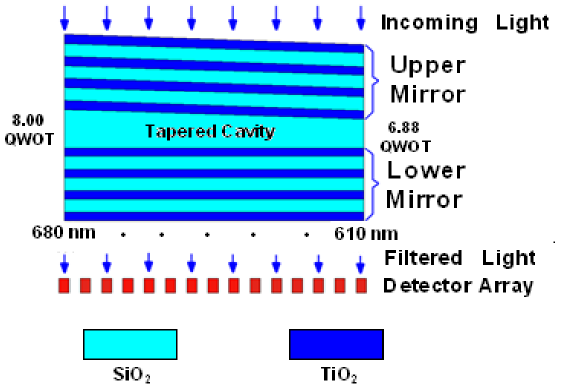

Fig. 8. The linear variable optical filter for the range of 610nm to 680nm

In figures 9,10,11,12 and 13 in order to fabricate a filter with eight cavity, the various stages of deposition are shown. SiO_2 and TiO_2 layers are used for making the top and the bottom mirrors. Three different masks are needed to create an eight-cavity array. The deposition time of the first mask is double than the second mask. The deposition time of the second mask is also double than the third mask. To make a 2^N-cavity array you need N different masks to do N deposition stages in the cavity layer.

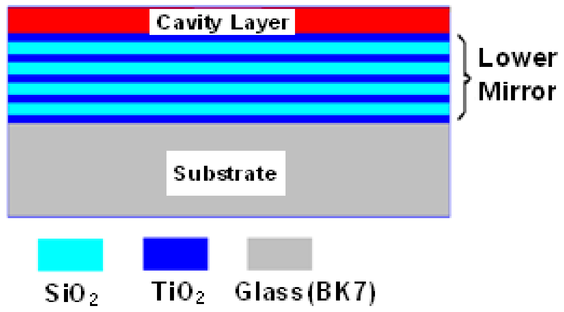

Fig. 9. First stage of deposition including substrate, lower stack and commom cavity layer

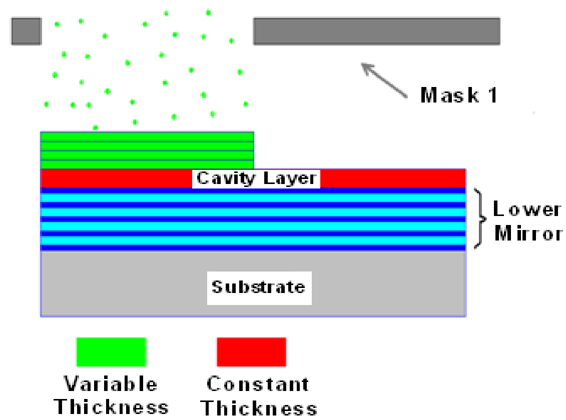

Fig. 10. Second stage of deposition on variable cavity layer by using of mask number 1

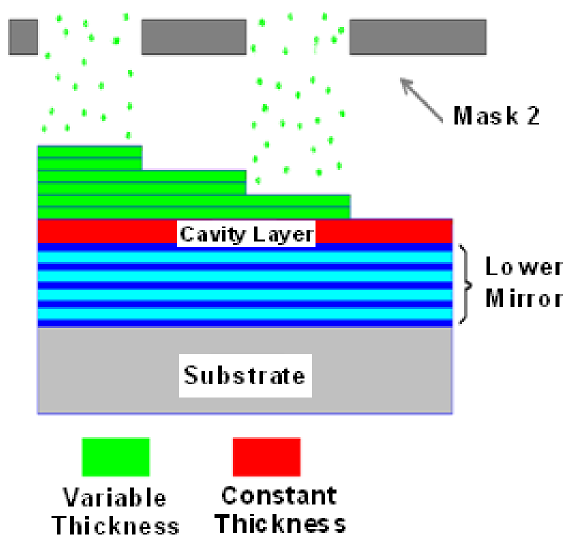

Fig. 11. Third stage of deposition on variable cavity layer by using of mask number 2

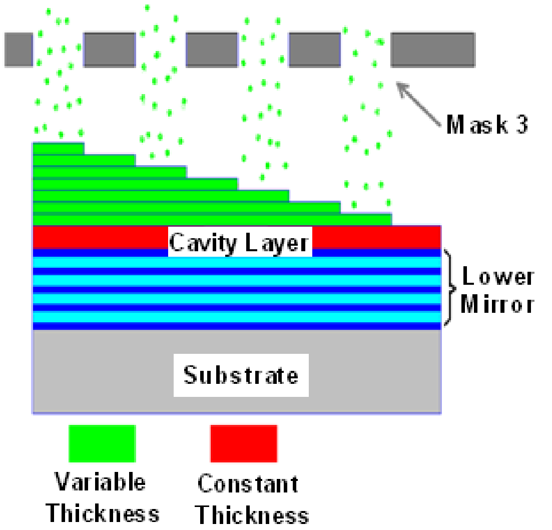

Fig. 12. Fourth stage of deposition on variable cavity layer by using of mask number 3

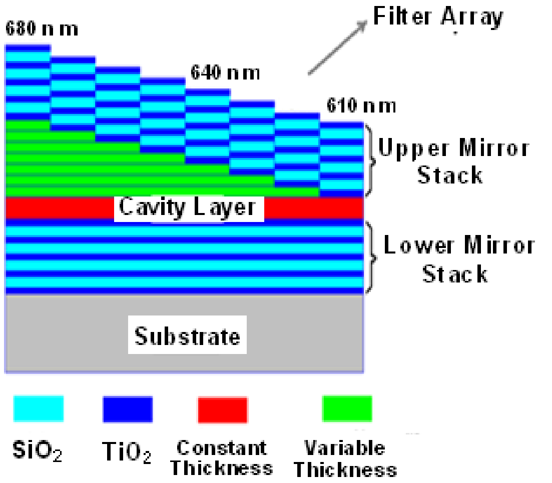

Fig. 13. Fifth stage of deposition on upper stack

III. MATHEMATICAL MODEL

Transfer Matrix Method (TMM) is used to describe optical properties of one dimension multi-layer structures. According to Figure 14, we consider a multi-layer structure so that a light beam incident enters the structure from the air with zero incidence angle and after passing through the intermediate layers, leaves the structure and goes into the end layer that its refractive index is n_s [12]. We assume that all layers are isotropic and non-magnetic and have the same properties or characteristic along all axis and incidence angle is zero. We suppose that the thickness of the end layer is very larger than the previous layers so that the amplitude of the reflected component dependent to the optical wave will be taken into account zero in the final layer.

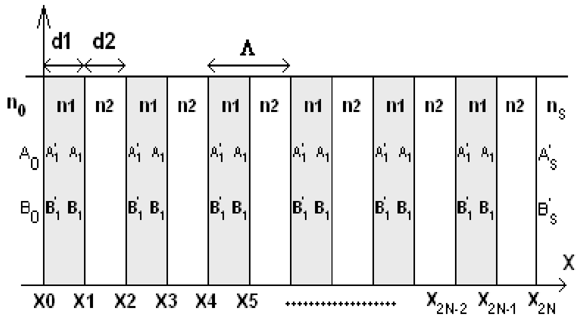

Fig. 14. Multilayer structure with two types of refractive index

Let A_0 and A'_S represent the amplitude of right-traveling wave and B_0 and B'_S be that of the left-traveling one. Indexes 0 and S represent respectively the first layer and the last layer according to equations 1 and 6.

The transfer function T can be written as equation 8.

$$E(x) = A_0 e^{-ik_0 x} + B_0 e^{ik_0 x} \tag{1}$$

Expressions of P, D and D^{-1} are the propagation matrix, the dynamical matrix and the inverse dynamical matrix of each layer in the filter structure respectively.

$$\begin{pmatrix} A_{m-1} \\ B_{m-1} \end{pmatrix} = (D_{m-1})^{-1}(D_m)(P_m)\begin{pmatrix} A_m \\ B_m \end{pmatrix} \tag{2}$$

D matrix in the above equation:

$$D_m = \begin{cases} \begin{pmatrix} 1 & 1 \\ n_m\cos(\theta_m) & -n_m\cos(\theta_m) \end{pmatrix} & \text{for TE wave} \\ \begin{pmatrix} \cos(\theta_m) & \cos(\theta_m) \\ n_m & -n_m \end{pmatrix} & \text{for TM wave} \end{cases} \tag{3}$$

Also propagation matrix shown as:

$$P_m = \begin{pmatrix} e^{ik_m d_m} & 0 \\ 0 & e^{-ik_m d_m} \end{pmatrix} \tag{4}$$

The parameter k_m related to angular frequency and light velocity in equation (5):

$$k_m = n_m \frac{\omega}{c} \cos\theta_m \tag{5}$$

where n_m is refractive index of layers and c is the light propagation velocity. The relation between A_0, B_0 and D is:

$$\begin{pmatrix} A_0 \\ B_0 \end{pmatrix} = D_0^{-1}\left[D_1 P_1 D_1^{-1} D_2 P_2 D_2^{-1}\right]^N D_S$$

$$\begin{pmatrix} A_0 \\ B_0 \end{pmatrix} = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}\begin{pmatrix} A'_S \\ B'_S \end{pmatrix} \tag{6}$$

In other words transmission coefficient could be calculated as:

$$t = \left.\begin{pmatrix} \dfrac{A_S}{A_0} \end{pmatrix}\right|_{B_S=0} \quad \Rightarrow \quad t = \frac{1}{M_{11}} \tag{7}$$

Then the final equation for transmission is:

$$T = \frac{n_s \cos\theta_s}{n_0 \cos\theta_0} |t|^2 = \frac{n_s \cos\theta_s}{n_0 \cos\theta_0} \left| \frac{1}{M_{11}} \right|^2 \qquad (8)$$

IV. SOFTWARE FOR THIN FILM CALCULATION

Optical properties of a multilayer dielectric structure can be described by the reflection spectrum, the transmission spectrum and the absorption spectrum as the band graphs. TFCalc software can be used to draw the band graph for two types of polarization and all radiation angles. All graphs in this paper are obtained by using TFCalc software. This software has been developed by Software Spectra and can be used for the design optimization of the multilayer structures[13], [14].

V. CONCLUSION

In the linear variable optical filter that its structure was described in this paper, for fixing 2^N cavities side by side in one direction, we must use N masks for the deposition stage. For example, in a certain range of visible spectrum in order to transmit 64 (2^6) wavelengths, 6 steps of mask making are necessary for creating a 64-cavity filter.
In this type of linear filter, by decreasing the thickness of the cavity layer, the central wavelength of the transmitted spectrum is shifted towards lower wavelengths but the band width (FWHM) does not remain constant and partly increases.

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