Notch filters design with enhanced performance

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Abstract. This research describes new designs of notch filters for visible region (400-800 nm). These designs were constructed by using new creative materials systems that provided good performance and environmental stability. According to our approach to design, an optimal performance of notch filters was presented. Which concerned to use the suitable number of layers with adjusting the thickness of each layer and trying to reach the thinner limit which meant to be an advanced achievement in design. Designs were clarified an optimum performance at stopband and passband with narrow blocking range between the low and high pass bands.

1. Introduction

Notch filters (also called Minus filters) are filters that reject a band of wavelengths while transmitting the high and low wavelengths [1,2]. A novel characterization of a notch filter is illustrated in Figure 1 by blocking or rejecting a narrow wavelength range (stopband) and transmitting efficiently the high and low bands of wavelength (called passband). The stopband and passband that ranged from $\lambda_1$ to $\lambda_2$ are defined by the reference wavelength $\lambda_o$.[1,3]

The optical performance of notch filters various mechanisms control notch filter performance and it may be constructed in various configurations forms. however, these filters employ multilayer interference instead of absorption to reject the desired stop band by being able to reflect some wavelengths and transmit others to enable the required performance [4-7].

Notch filters are usually employed when it is required in applications requiring the rejection of an electromagnetic wavelength band while passing low and high parts of the spectrum. So these filters would be useful in defense systems against laser weapons where only the laser spectral band is rejected while transmitting others[1], also such filters are frequently task of an optical system device for astronomical observations and remote sensing of the earth. Where selection of a spectral band from abroad incoming spectrum is required[8,9].

The new stacks that presented in this paper provide notch filter with narrow blocking range between the low and high pass bands on both sides of the stopband. This was achieved by using superior materials systems by adjusting the thickness of coating layers where the work included refinement of each individual layer of construction stacks with using specific materials.
2. Formulation of optical performance

This study is accomplished through the calculation of the system’s characteristic matrix to obtain the transmission profile for a multi-layered configuration on a substrate. Consider a multilayer coating consisting of q thin film layers with an index of refraction $n_r$ and the actual thickness of the $r$-th layer $d_r$. Simply the characteristic matrix is obtained by the product computation of the matrices to all layers in the assembly taken in the correct order [10-12].

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

Where, B and C are the input surface magnetic and electric tangential components of the electromagnetic wave respectively, $n_s$ the substrate index of refraction and $\delta_r = 2\pi n_r d_r/\lambda_o$, $\lambda_o$ represent to the design (reference) wavelength.

$\begin{bmatrix} B \\ C \end{bmatrix}$ is called the optical system characteristic matrix.

According to characteristic matrix calculations spectral transmittance profile of the multilayer system is given as follow:

$$T = \frac{4n_o \text{Re}(n_s)}{(n_o B + C)(n_o B - C)} \tag{2}$$

Re($n_s$) is the substrate's index of refraction (the real part) and $n_o$ refractive index of the incident medium.

In this paper, the transmission performance of notch filters design calculates by using MATLAB software according to the equations above.

3. Designs and discuss the results

In this work, we use a system consisting of two and three materials in constructing of the notch filter design stacks. These innovative designs of notch filters were obtained by utilizing new promising materials systems in designs. The optical performance is characterized by nearly narrow stopband with transmittance equal to zero, high transmittance on both sides of the stopband with an elimination of ripples, and get the high transition between passband and stopband as is shown in figures (2,3,4).

Figure.2 demonstrates the behaviour of a new design of notch filter. In this design, we used the system of three materials consisting of Zinc Sulphide (ZnS), Magnesium fluoride (MgF$_2$) and Silicon monoxide (SiO) deposited on the glass as a substrate.

The structure composed (29) layers of ZnS is referred by H layers (refractive index $n=2.3$) and MgF$_2$ is referred by L layers (refractive index $n=1.38$) and SiO is referred by M layers (refractive index $n=1.9$). H, M and L represent to the quarter wave optical thickness of high, medium and low index of layer coating respectively. Design wavelength $\lambda_o = 530$ nm has been used in calculations.

In this design, it is taken into account the preparation of coating layers with a specific thickness by adopting our own strategy that based on using a suitable number of layers by adjusting every layer thickness by specific coating and try to get small overall thickness which is important in manufacturing. The modified thickness of an individual layer that we adopted is one quarter wavelength thickness dual quarter wavelength thickness and triple quarter wavelength thickness with
keeping the overall thickness limited within agreement range. As a result in this work relatively narrow stopband is achieved within a narrow wavelength range of 50 nm and high transmittance in the wide passband with negligible ripples. Optimized performance in passband was obtained.

Figure 3 represents another successful design of notch filter. We used the system of three materials consisting of Zirconium dioxide ($\text{ZrO}_2$), Magnesium fluoride ($\text{MgF}_2$) and Aluminium Oxide ($\text{Al}_2\text{O}_3$). The structure of design composed (28) layers of $\text{ZrO}_2$ is referred by H layers (refractive index $n=2.05$), $\text{MgF}_2$ is referred by L layers (refractive index $n=1.38$), $\text{Al}_2\text{O}_3$ is referred by M layers (refractive index $n=1.6$) and glass is the substrate material. Design wavelength $\lambda_o=550\text{nm}$ has been used. Also in this design, we adopted coating layers their thickness wereconstructed using one quarter wavelength thickness dual quarter wavelength thickness and triple quarter wavelength thickness, with keeping the overall thickness limited within agreement range. This new materials system presented good progress in the optical performance of notch filter, it is clear here that by employing a larger number of layers with specific differences in thickness of layers assisted to get better optical performance. We got optimal behaviour in passband with reducing the ripples, very narrow stopband within the range less than 30 nm.

Advanced and optimized performance of notch filter presents in Figure 4. We have made significant progress in the design using two materials system. The structure consists of 29 layers of $\text{ZnS}$ (refractive index $n=2.35$) and $\text{MgF}_2$ (refractive index $n=1.38$), which is indicated by H and L layers respectively, rang wavelength (450-1600nm), and 780nm is (design wavelength).

Optical performance of this design is characterized by high transmittance in the passband with the disposal of ripples, stopband is narrow in comparison with the two sides of the wide ranges of the passband, one side is located between (450-700 nm) and the other extending from 850 nm to 1600 nm.

4. Conclusions

This paper has concerned to design new configuration stacks of the notch filter. The results showed an optimal performance of notch filters for the visible region. These innovative designs of notch filters were obtained by using new promising materials systems in designs. The systems consisting of two and three materials in constructing of the notch filter stacks. On adopting of strategy that using a suitable number of layers by adjusting every layer thickness keeping the thickness limited within agreement range. The specific thickness of the individual layer that we adopted is one quarter wavelength thickness dual quarter wavelength thickness and triple quarter wavelength thickness. Also, we achieved a good progress by the ability to modify the thickness of each quarter wavelength thickness and made them thinner with using just two materials in constructing of the notch filter stacks where the final design seems to be optimum one.
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Figure 1. Single notch filter characteristic

Figure 2. Optical performance of notch filter for the configuration:
[Air | L 2M (3M 3L 3M) (3L 3H)² (3L 3M)²]Glass
Figure 3. Optical performance of notch filter for the configuration:
\[ \text{Air} \mid L 2H M 1.5L (3M3L)^2 (3H 3L)^8 (3M 3L)^2 \mid \text{Glass} \]

Figure 4. Optical performance of notch filter for the configuration:
\[ \text{Air} \mid 2.3236L 0.2548H 1.7156L 0.3256H 1.6504L 0.44H (1.5L 0.5H)^8 1.582L 0.3336H 1.7248L 0.2516H 1.7884L 0.1456H 1.556L \mid \text{Glass} \]