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Tunable Edge Filter as a Smart Energy Saving Window at the Hot Climates of the Baha Region in the Kingdom of Saudi Arabia

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Abstract: This Study demonstrated a design of one-dimensional photonic crystal (PC) structure consisting of alternate layers of Silicon dioxide (Sio_2) and Tantalum pentoxide (Ta_2O_5) that blocks infrared light and passes only light of short wavelengths. Results show a new design for optimal edge filter of optical short-wave pass (SWP) filter that can be used as a smart energy saving window. Alaqiq and Almakhwah are hot climate provinces at Albaha region in Kingdom of Saudi Arabia. They have been taken as examples for this study. The design was done with the computational help of optimization using the "Essential Macleod" software. The mean polarized light mode has been contained a transmittance greater than 98% in both summer and winter solstices in the visible region and more than 40% of the amount of sun energy has entered in winter from the infrared region which has been reflected (stopped) in summer. That results in a 0.025-0.175 µm photonic band gap (PBG) shift in the direction of short wavelengths by increasing the angle of incidence.

Keywords: Design edge filter, SWP filter, Characteristics Matrix, Needle optimization technique, Smart energy saving window.

INTRODUCTION

Photonic Crystals (PCs) or Photonic Band Gap (PBG) materials are a new class of optical materials with a periodic modulation in the dielectric constants on the length scale comparable to the optical wavelength. These artificial materials create a range of forbidden frequencies called photonic band gap in which propagation of electromagnetic (EM) waves is completely prohibited in a manner analogous to the formation of electronic band gaps in semiconductors [1,2].

Optical interference filter is the preferred type of optical coatings, which use the phenomenon of interference waves [3,4]. Such filters consist of multi-layered thin films deposited on substrates, and have the property of being able to reflect a range of wavelengths and transmit others[3,5]. Useful application of such coatings is the edge filters [5-9].

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 wave-length, known as the edge wavelength, the high transmittance in the passband is usually desired [6, 10,11]. Edge filters are divided into two main designs, long-wave pass (LWP) and short-wave pass (SWP) [7,8,12]. One design has the passband on the high wavelength side of the stop band, while the other one is on the low wavelengths side. The designs of the edge filters are the following[13]:

n_o [0.5H $(LH)^A$ L 0.5H] n_s (High λ pass)

n_o [0.5L $(HL)^A$ H 0.5L] n_s (short λ pass)

Where H and L are quarter-wave optical thickness of a high index layer and a low index layer respectively. The double–layer combination (HL) stack between massive substrate (n_S) and air (n_O) is repeated A times. A is also called the “order of periodicity”. In the analytical approach, the ripples appear in the passband because of the mismatching between the coating materials and the surrounding medium[14,15]. These ripples are severe and the performance of the filter design would be quite a difficult task. These filters are widely used for various optical applications, especially in wavelength division multiplexers (WDM), optical fiber communication systems, and multimedia color projection display[16, 17,18].

In this paper we apply a technique that depends on the needle optimization as a synthesis method and characteristics matrix to design optimal edge filter of short-wave pass for visible-near IR region (0.4-1.1 μm) [19,20,21].The design was done with the computational help of optimization using the “Essential Macleod” software [11]. We present a method of building a high-optical quality short-wave pass filter, as the smart energy saving windows in buildings and other applications that can significantly reduce sun energy at hot climates. Alaqiq and Almakhwa are hot climates provinces at Albaha region in Kingdom of Saudi Arabia. They have been taken as examples to study this optical low pass filter as a smart energy saving window which changes its optical properties through the change in the incident angle of sun rays in summer and winter solstices , and they can revert to their original state by an angle reversal.

OPTICAL PASS FILTER MATRIX CALCULATIONS

In this study modeling 1D photonic crystal, as an optical short-wave pass filter, has been carried out using Characteristics Matrix to determine the spectral transmittance profile for multilayer structures on a substrate [4,11,18]. Figure (1) shows the multilayer structure of an optical filter. Characteristics matrix are the assembly of q thin film layers. Simple characteristic matrix is the product of the individual matrices for the individual layers of the assembly taken in the correct order, i.e.

$$\begin{bmatrix} B \\ C \end{bmatrix} = \left\{ \prod_{r=1}^{q} \begin{bmatrix} \cos\delta_r & (i\sin\delta_r)/\eta_r \\ i\,\eta_r \sin\delta_r & \cos\delta_r \end{bmatrix} \right\} \begin{bmatrix} 1 \\ \eta_m \end{bmatrix} \qquad [1]$$

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

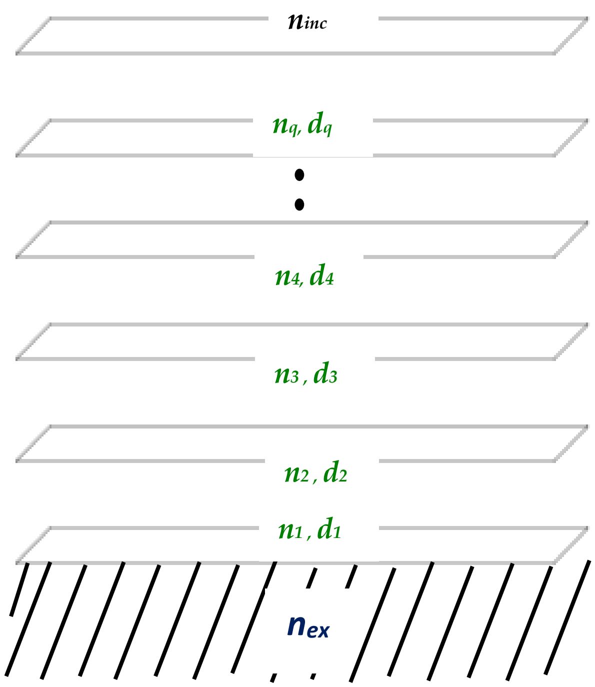

Figure (1): Multilayer Optical Filter

$$\delta_r = 2\pi n_r d_r \cos\Theta / \lambda \qquad [2]$$

δ_r is the phase shift of the wave inside the layer of refractive index n_r and physical thickness d_r .

Θ is the angle of incident light.

λ is the wavelength of light in vacuum.

η_r is the pseudo index of the layer (a tilted optical admittance of the layer).

η_m is the pseudo index of the substrate or emergent medium.

The order of multiplication is important. If q is the layer next to the substrate, then the order is

$$\begin{bmatrix} B \\ C \end{bmatrix} = [M_1][M_2]\ldots[M_q]\begin{bmatrix} 1 \\ \eta_m \end{bmatrix} \qquad [3]$$

M_1 indicates the matrix associated with layer 1, and so on. As in the case of a single surface, η_o must be real for reflectance (R) and transmittance (T) to have a valid meaning. With that proviso, then

$$R = \left(\frac{\eta_0 B - C}{\eta_0 B + C}\right)\left(\frac{\eta_0 B - C}{\eta_0 B + C}\right)^* \qquad [4]$$
$$T = \frac{4\eta_0 \operatorname{Re}(\eta_m)}{(\eta_0 B + C)(\eta_0 B + C)^*}$$

NEEDLE SYNTHESIS TECHNIQUE

Numerical methods are the most widely used techniques for the solution of complicated spectral problems that cannot be solved with other methods, and can be applied to the design of coatings with very complicated specifications [19,20,23].The problem of optical coating design can be formulated as an optimization problem [24,25]. The performance of the design during the optimization procedure is improved by minimizing the merit function that measures the discrepancy between the target and solution [26, 27]. The most important merit function (MF) form is that proposed by Dobrowolski which is defined as [24, 28]:

$$MF = \left[\frac{1}{m}\sum_{i=1}^{m}\left(\frac{B_i^T - B_i}{\delta B_i}\right)^k\right]^{\frac{1}{k}} \qquad [5]$$

The merit function has been minimized by modifying several design parameters like the thickness and refractive indices of the individual layers [29]. Needle synthesis is the most commonly and efficient optimization design technique used. It’s a powerful method for producing designs with complex performance [9,15,19-21,24,30].

The principal feature of needle optimization technique is that the choice of starting design is not a problem. The essence of the 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 [24]. 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 insertion of the needle layer no longer affects the decrease in the merit function [4, 11, 31].

RESULTS AND DISCUSION

In this section, we have designed an edge filter of short-wave pass (SWP) filter by numerical optimization method (needle technique) using the Essential Macleod software. The optical performance of the filter has been studied for visible-near IR region (0.4–1.1μm).The designed dielectric edge filter is composed of alternating Tantalum pentoxide ($Ta_2 O_5$, n_H =2.14) and Silicon dioxide (Sio_2, n_L =1.46) layers and substrate is glass with n_{glass} = 1.52; the design wavelength λo = 0.550 μm.

Studying the properties of the filter by varying the angle of incidence of light at mean polarized light, gives us an important application for this filter. It can be used as a smart energy saving window. Alaqiq and Almakhwah are hot climate provinces at Albaha region in Kingdom of Saudi Arabia. They have been taken as examples for this study. **Table (1)** shows the incident angles of the sun at summer and winter solstices measured at noon time for them [32, 33].

Table (1): the incident angles of the sun at summer and winter solstices measured at noon time for Alaqiq and Almakhwah provinces.

Solstice	**Day/Month**	**Alaqiq province**	**Almakhwah province**
		Angle /deg	**Angle /deg**
Summer	21-Jun	4.73	5.24
	21-Jul	4.65	4.9
	21-Aug	9.18	9
	21-Sep	19.77	19.27
Winter	21-Dec	43.79	43.28
	21-Jan	40.54	40.05
	21-Feb	31.41	30.94
	21-Mar	20.93	20.48

Table (2) shows the maximum temperature in summer and winter solstices measured for Alaqiq and Almakhwah, as well as Albaha region in Kingdom of Saudi Arabia[34, 35]. Before the design optimization, the performance at normal polarization is shown in Figure (2). The curve shows the transmittance profile of 37 layers of short-wave pass (SWP) filter with total physical thickness 4.708 μm where in the visible region, the pass band had an average transmittance Tav = 96% in 0.4 -6.95 μm spectral range, for normal incidence. In the infrared region, the stopband had an average transmission of Tav = 0.6% in 7.35-1.085μm spectral range.

Table (2): The maximum temperature in summer and winter solstices measured for Alaqiq and Almakhwah

Solstice	Month	Alaqiq province	Almakhwah province
		Maximum Temperature (°C)	Maximum Temperature (°C)
Summer	June	36.1	41.6
	July	36	41
	August	35.1	40.1
	September	35.3	40
Winter	December	23.9	30.8
	January	23.1	29.7
	February	25.2	31.2
	March	28.1	33.9

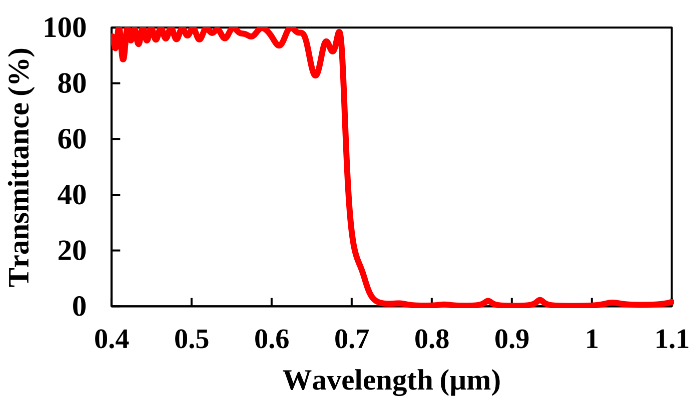

Figure (2): The performance of optical SWP filter at normal polarization before optimization.

The design has been optimized using Essential Macleod software[11]. The needle technique was used in the present study. The performance of the design after optimization is shown in figure (3), which offers the improved optical performance of the layers of short- wave pass (SWP) filter. The curve shows the transmittance profile of 41 layers with total physical thickness 4.775 µm where the coating layers increased to get optimal short-wave pass (SWP) filter as shown in figure (3). In the visible region, the pass band had an average transmittance greater than 99 % in 0.4-0.695 µm spectral range, for normal incidence and in the infrared region, the stop band had an average transmission of Tav = 0.6% in 0.735-1.085 µm spectral range.

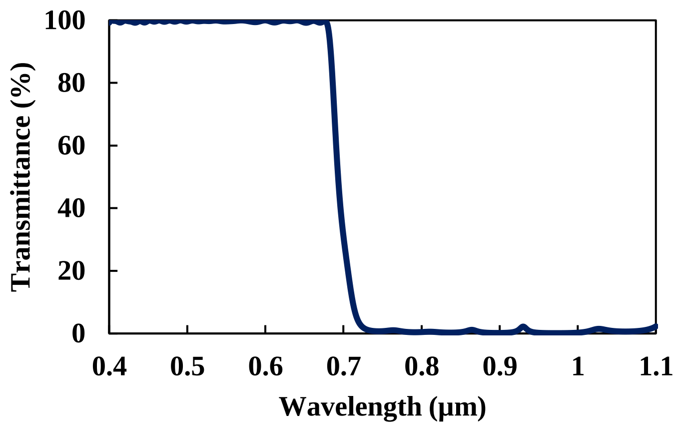

Figure (3): The performance of optical SWP filter at normal polarization using the needle technique.

The transmission spectrum of the optimal design has been studied in detail by varying the angle of incidence of light at mean polarized light (mean-pol) in summer and winter solstices, one for Alaqiq province and one for Almakhwah province at Albaha region in Kingdom of Saudi Arabia.

Figures (4A and B) show the contour and 3D plots. They show the general aspect of transmittance with varying the angle of incidence of light through the optimal design. By increasing the angle of incidence the stop band shifts in the direction of short wavelengths permitting the transmission of the infrared radiation at high angles (in winter solstice).

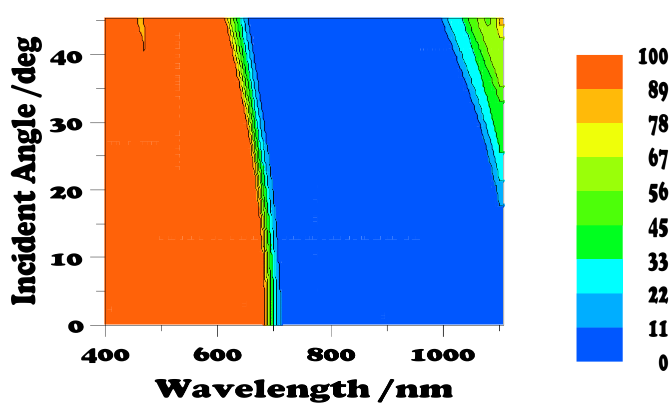

Figure (4A): Contour plot for the transmittance in Summer-Winter Solstices by varying the angle of incidence.

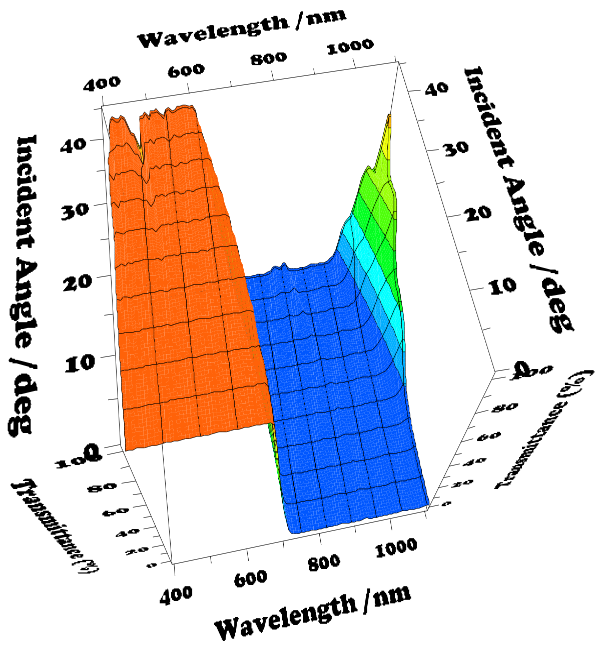

Figure (4B): 3D plot for the transmittance in Summer-Winter Solstices by varying the angle of incidence.

(a) For Alaqiq Province: Figure (5) shows a significant reflection (stop) of sun energy (in the infrared range) which has been noticed in summer time. Mean polarized light shows a transmittance greater than 99% in the visible spectral range during summer solstice **(Figure 5)** and greater than 98% in winter solstice **(Figure 6)**.

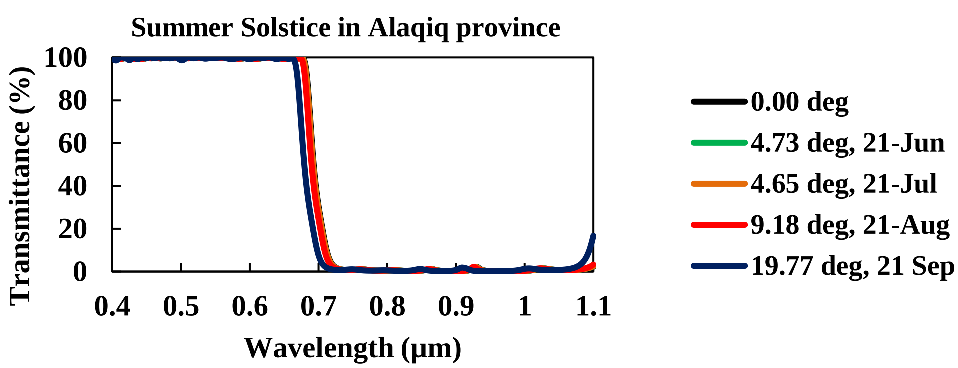

Figure (5): Transmittance profile for optimal low pass filter in summer solstice in Alaqiq province.

As shown in Figure (6) by increasing the angle of incidence, the stop band shifts in the direction of short wavelengths permitting the transmission of the infrared radiation in winter. It results in a 0.025–0.175 μm photonic band gap (PBG) shift in the direction of short wavelengths by increasing the angle of incidence. The transmittance on 21 December is more than 41 % , in the range from 1μm to 1.100 μm, allowing IR for space heating during that time of the year and then it decreases reaching 6% on 21 of March.

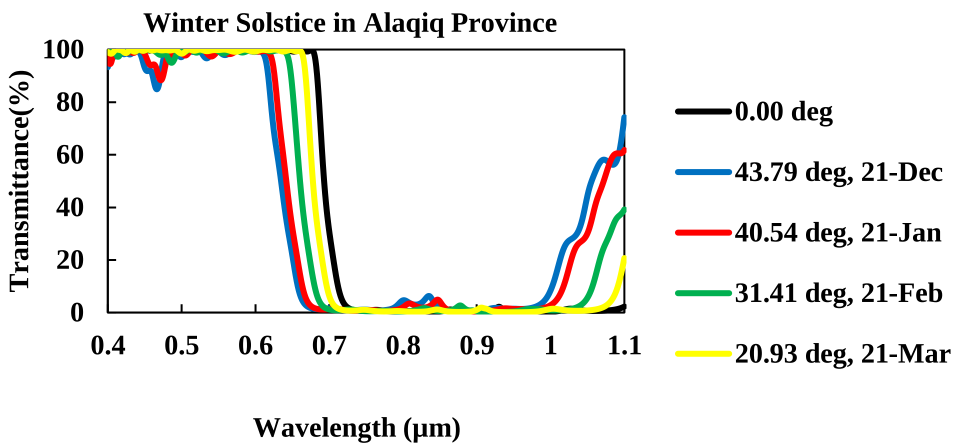

Figure (6): Transmittance profile for optimal low pass filter in winter solstice in Alaqiq province.

after the optimization. As shown in figures (7,8), the quality factor Q increases as the angle of incidence Θ increases at the mean-polarized light. This means that the PBG decreases by increasing the angle of incidence which permits the amount of sun energy to enter in winter solstice. Q can be used as a probe for the variation of the size of the PBG with the angle of incidence of the sun i.e. from summer solstice to winter solstice.

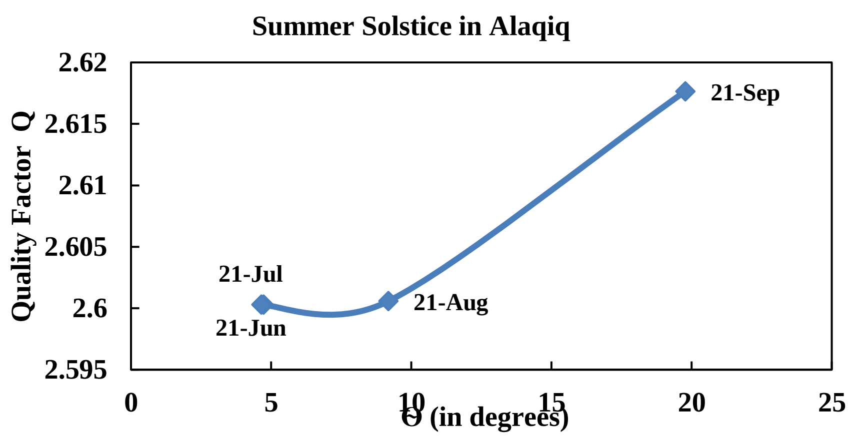

Figure (7): Quality factor Q vs The angle of incidence Θ at mean polarized light at summer solstice in Alaqiq.

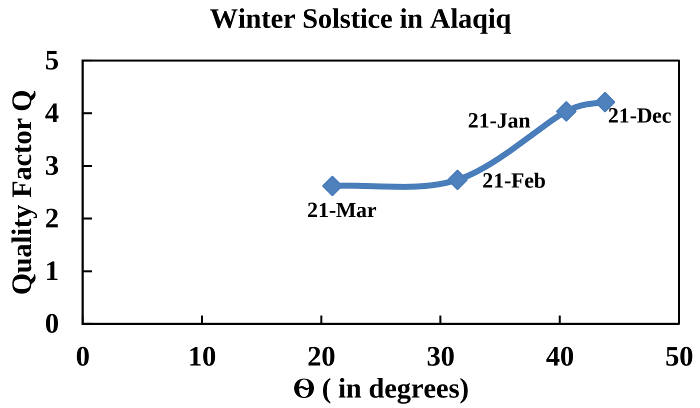

Figure (8): Quality factor Q vs The angle of incidence Ɵ at mean polarized light at winter solstice in Alaqiq.

(b) For Almakhwah Province : Figure (9) shows that same results have been obtained as in Alaqiq province during summer. As shown in Figure (10), by increasing the angle of incidence the stop band shifts in the direction of short wavelengths permitting the transmission of the infrared radiation in winter. This results in a 0.025–0.170 µm photonic band gap (PBG) shift in the direction of short wavelengths by increasing the angle of incidence. The transmittance on 21 December is more than 40 % in the range from 1µm to 1.1µm, allowing IR for space heating during that time of the year and then it decreases reaching 5.5% on 21 March.

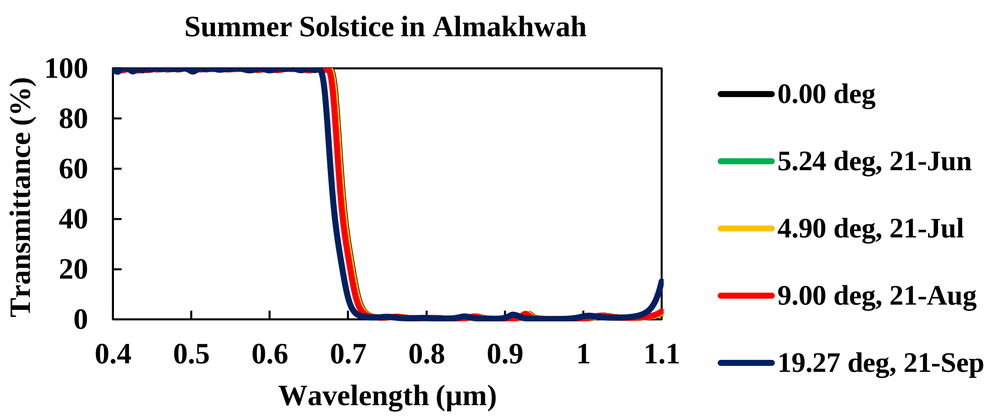

Figure (9): Transmittance profile for optimal low pass filter in summer Solstice in Almakhwah province.

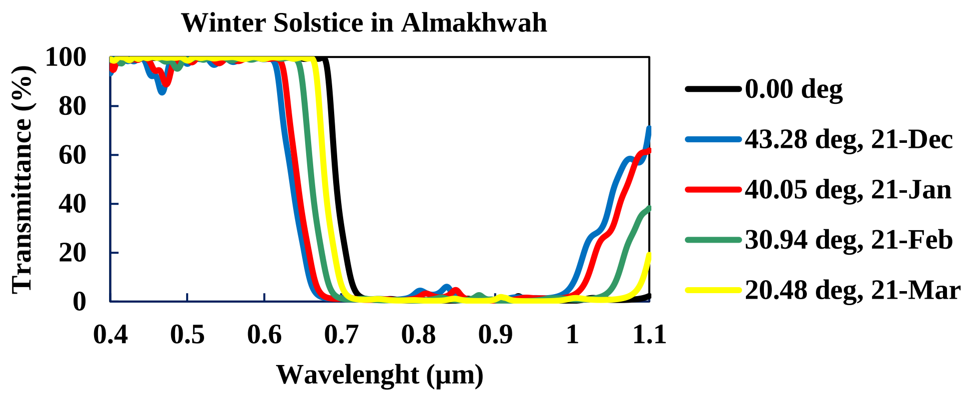

Figure (10): Transmittance profile for optimal low pass filter at winter solstice in Almakhwah province.

As shown in figures (11,12), The quality factor Q increases as the angle of incidence ϴ increases at the mean-polarized light which it means decreasing in the PBG with increasing the angle of incidence which permits amount of sun energy to enter in winter solstice.

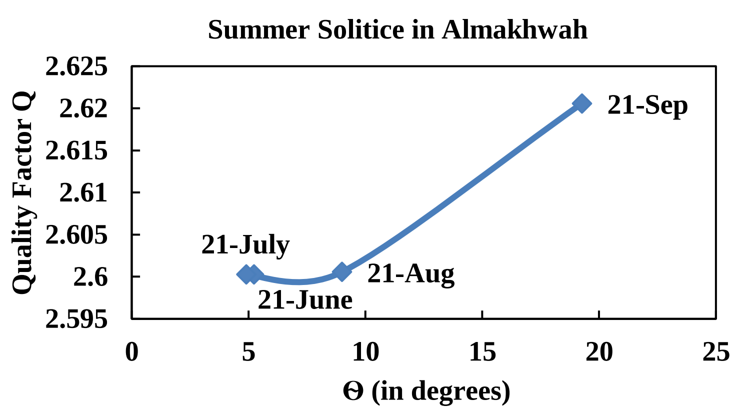

Figure (11): Quality factor Q vs The angle of incidence ϴ at mean polarized light at summer solstice in Almakhwah.

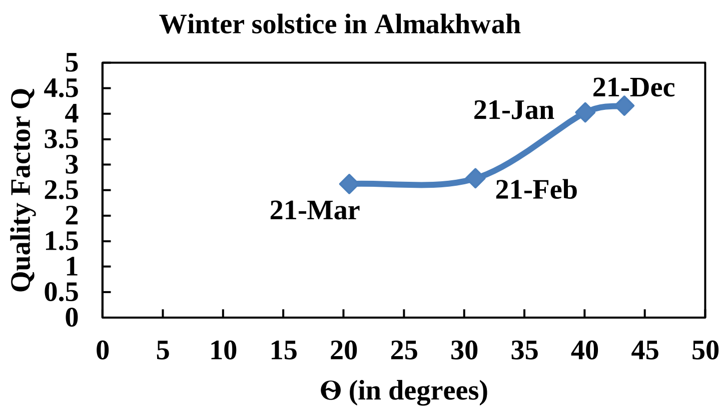

Figure (12). Quality factor Q vs the angle of incidence Ɵ at mean polarized light during winter solstice in Almakhwah.

By comparing the study of the optimal design of short-wave pass (SWP) filter in Alaqiq and Almakhah provinces, it is clear that the results are nearly the same except a minor increase of IR energy entered during winter in Alaqiq more than Almakhwah.

CONCLUSION

In this Study, the needle technique has been applied as a synthesis method. The characteristics matrix was also used in designing an optimal edge filter of short-wave pass (SWP) for visible-near IR region (0.4-1.1µm).The tuning of SWP filter that was obtained and its optical properties that had been studied can be used as a smart energy saving window. Alaqiq and Almakhwa have been taken as examples for this study. They are hot climates provinces at Albaha region in Kingdom of Saudi Arabia. Mean polarized light mode has shown a transmittance greater than 98% during both summer and winter solstices in the visible region and more than 40% amount of sun energy entered in winter from the infrared region which has been reflected (stopped) in summer. This results in a 0.025–0.175 µm photonic band gap (PBG) shift in the direction of short wavelengths by increasing the angle of incidence. it is clear that the results are nearly the same except a minor increase of IR energy entered during winter in Alaqiq more than Almakhwah.

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REFERENCES

1. E. Yablonovitch, "Inhibited Spontaneous Emission in Solid-State Physics and Electronics", Phys. Rev. Lett., 1987,58 (20), 2059-2062.
2. S. John, "Strong localization of photons in certain disordered dielectric super lattices" Phys. Rev. Lett., 1987,58 (23), 2486-2489.
3. M. A. Kats, J. Byrnes, R. Blanchard, M. Kolle, P. Genevet, "Enhancement of absorption and color contrast in ultra-thin highly absorbing optical coatings", Appl. Phys. Lett. 2013, 103 : 101104 .
4. H. A. Macleod, "Thin-film optical filters", 5th edtion, CRC press Taylor and Francis group, 2017.
5. A. Thelen, "Design of optical interference coatings", McGraw-Hill, 1989.
6. H. G. Rashid, A. Nazar, and M. Al-Amshani,"Design and fabrication of nano-layered optical edge filter", Journal of Materials Science and Engineering A, 2012, 2 (2).
7. E. Abdel-Rahman, K.Bashir, R. Ghannam, and A. M. Shaarawi " Design of an infrared shield device based on 1D photonic crystal" META'10, 2nd International Conference on Metamaterials, Photonic Crystals and Plasmonics,Cairo, Egypt, February22-25, 2010.
8. E. Abdel-Rahman, K.Bashir, R. Ghannam, and A. M. Shaarawi "Design and optimization novel optical low pass filters of a 1D-photonic crystal using TiO2/ SiO2 thin films" META'10, 2nd International Conference on Metamaterials, Photonic Crystals and Plasmonics,Cairo, Egypt, February22-25, 2010.
9. Alaa Nazar abudalghaffar, Narmeen Ali Jasem, "Study design edge filter using synthesis needle technique", International Journal of Scientific & Engineering Research, 2015, 6 (5).
10. R. R. Willey,"Constrained optimization of band edge filter matching layers", proceeding of SPIE, 1999,3738, 549-553.
11. H. A. Macleod, "Optical thin films", Thin film center Inc, 2017.
12. R. R.Willey, "Field guide to optical thin film", SPIE PRESS, Bellingham, Washington, 2006.
13. Kan Yu, Xiao-yang Zhou, Jia-qi Wang, Jing-jing Xu, and Juan-juan Yin, "A non-polarization short-wave-pass thin film edge filter", Optoelectronics Letters, 2014, 10 (4), 247-249.
14. Henrik Fabricius," Gradient-index filters: designing filters with steep skirts, high reflection, and quintic matching layers", Appl. Opt., 1992, 31(25).

15. A.V. Tikhonravov, M. K. Trubetskov, and G. W. DeBell, "Application of the needle optimization technique to design of optical coatings", Appl. Opt., 1996, 35 (28), 5493–5508.

16. G.U. Pei-fu and Z. Zhen-rong, "Design of non-polarizing thin film edge filters", J. Zhejiang Univ. (SCIENCE A), 2006,7 (6), 1037-1040.

17. Hongji Qi, Ruijin Hong, Kui Yi, Jianda Shao, and Zhengxiu Fan, "Nonpolarizing and polarizing filter design", Appl. Opt., 2005, 44 (12), 2343-2348.

18. Jinn-Moon Yang and Cheng-Yan Kao, Efficient evolutionary algorithm for the thin-film synthesis of inhomogeneous optical coatings, Appl.Op, 2001, 40 (19), 3256-3267.

19. Jinn-Moon Yang and Cheng-Yan Kao, An evolutionary algorithm for the synthesis of multilayer coatings at oblique light incidence, Journal Of Light Wave Technology, 2001, 19 (4).

20. Li Li and J. A. Dobrowolski, "Computation speeds of different optical thin-film synthesis methods", Applied Optics, 1992, 31 (19), 3790-3799.

21. S. Furman and A. V. Tikhonravov, "Basics of Optics of Multilayer Systems", Gifsur-Yvette Cedex. France: Editions Frontieres, 1992.

22. H. M. Liddell, "Computer aided techniques for the design of multi-layer filters", Adam Hilger Ltd, ISBN 0-85274-233-9, 1981, 2.

23. J. A. Dobrowolski and R. A. Kemp, "Refinement of optical multilayer systemswith different optimization procedures" Appl. Opt, 1990, 29 (19), 2876-2893.

24. S. Larouche and L. Martinu, "OpenFilters: open-source software for the design, optimization, and synthesis of optical filters", Appl. Opt., 2008, 47 (13).

25. J. A. Dobrowolski and R. A. Kemp, "Refinement of optical multilayer systemswith different optimization procedures" Appl. Opt, 1990, 29 (19), 2876-2893.

26. Gang Bao and Yuliang Wang, "Optimal design of antireflection coatings with different metrics", J. Opt. Soc. Am., 2013, 30 (4).

27. J. A. Dobrowolski, "Completely automatic synthesis of optical thin-film systems", Appl. Opt, 1965, 4(8), 937-946.

28. M. G. Turner and K. J. Garcia, "Optimization using rational Bézier control points and weighting factors",Proc. of SPIE , 2008, 7061.

29. I. Ya. Yaremchuk, V.M. Fitio, Ya. V. Bobitski, "New design of interference band-pass infrared filter", Opto-Electronics Review, 2011, 19 (2), 193-197.

30. H. Fabricius, "Synthesis and functioning of smart coating for application in compact instruments and sensors", Light and optics at DELTA, 2001.

31. James D. Rancourt, "Optical thin films IV: New developments", Proc. SPIE, 1994, 2262.
32. https://www.suncalc.org , 2018.
33. http://www.susdesign.com/sunangle/ , 2018.
34. https://en.climate-data.org/location/550534/ , 2018.
35. https://en.climate-data.org/location/550512/ , 2018.

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