Volume 2(2): 2024, Page 9-17

Design and Analysis Performance HL-Narrow FWHM Band Pass Filters for Mid Infrared Transmitting Materials

Harakat Mohsin Roomy[1]
Mohammed Shareef Mohammed[2]

[1] Ministry of education, Baghdad
[2] Ministry of Education Salah al-Din Iraq
* muhshr@gmail.com; Tel.: (009647837708936)

Abstract: Narrow band pass filters are designed to isolate a narrow region of the Mid infrared region. A new design accomplished using theoretical computation adopting MATLAB-software, already depends on characteristic matrix theory. With prescribed Stack of designs, the analyze band-pass filters wavelength range from 3000 to 5000 nm and the design wavelength 4000nm for normal incident for radiation. In this paper, a design based on 4 groups of materials for multilayers dielectric as high / low index: SiC/Si3N4, HgS \HfO$_2$, CdS\ MgF$_2$, PbTe\ CdTe on a ZnSe substrate were used. Simulation is used to demonstrate and examine critical conditions for narrow pass band with high optical transmittance and lower bandwidth.

Keywords: Interference band pass filter, Mid-wave infrared (MWIR), Transmission, Multi-layers. MATLAB-software

1. Introduction

The key steps in producing thin-layer systems with specific properties are interference coating design and implementation [1]. In contemporary optics, interference thin-layer filters are crucial components that frequently determine the equipment's overall effectiveness [2]. Manufacturing coatings with the use of current technology should satisfy such requirements [3]. When it comes to display, sensing, optical communications, and imaging systems, the mid-wave infrared (MWIR) waveband (~3000-5000 nm) is useful because it can be used for detecting radiant thermal signatures and probe chemical species' molecular vibrations [4]. With good in-band transmissions (or blocking, in a case of the devices of band blocking), and good rejection outside bands of interest, infra-red filters that are utilized to assist define wave-length response of IR instruments are ideal[5] [6]. [7]. Narrowband-pass filters and broadband-pass filters are the two broad categories into which band-pass filters can be split. There is no clear distinction between the two types, and how one particular filter is described typically relies on the application and filters it is being compared to [1]. A combination of short wave pass and long wave pass filters is the best construction for the widest band-pass filter [8]. Other techniques, which create the pass and rejection bands from a single assembly of thin films, are utilized for narrower filters. Additionally, the filters' cut-off and cut-on transmittance properties should be extremely steep, and their transmittance at wavelengths other than the transmission wavelength should be extremely low [9]. The simplest thin-film optical band pass filters are made up of two multilayer dielectric mirrors and a single spacer (resonant cavity)

[1]. The triangular shape of single cavity band pass filters has a good transmission at the space's central wavelength [10]. The materials' relative indices, the material selected for the spacer layer, and the quantity of layers, or periods, in the mirror structures all affect the filter's bandwidth [7]. The alternating low- and high-index materials (N bi-layers) used in the dielectric band pass filters have an optical thickness of 0.25 waves, creating a spectrum "rejection region" [10]. For the wavelength range for which it is intended, this quarter wave stack will have strong reflectivity, and outside of this range, the reflectance rapidly decreases [9]. By simply adding layers, the stack's reflectance could be raised to an extremely high level, serving as the fundamental building block for many different types of filters [11]. A designed sequence regarding the thin layer filters (LH)^n is a repetition of the LH sequence n times, in which L and H stand for low- and high-index quarter-wave layers, respectively. The optical properties of the filters could be enhanced by the significant variation in refractive indices between materials. The wavelength, λmax, at which the maximum transmission occurs, the wavelength, λo, at which the filter pass band is symmetrical, or the band's spectral center can all be used to specify the position of the transmission band [12]. A common term used to describe the transmission properties of an optical band pass filter is FWHM (full-width-half-maximum), which measures the width of the spectrum at the wavelengths the filter passes in nanometers. Broadbands of narrow band pass filters are less than 0.06 of the wavelength's center value (measured at half-peak transmittance levels), minimum peak transmittance is greater than 80%, and the transmission bandwidth is 2.5 % of the wavelength [13]. High attenuation levels outside the passband (commonly < 0.1 %) are also present. [14] The degree of transmission and reflection, the size of the spectral range over which transmission, reflection, and the transition between them occur, and the polarization effects at off-normal angles of incidence are just a few of the coating performance properties that can be optimized using thin-layers design software and optical thin-film theory [15]. The quantity of boundaries, the variation in refractive index across each boundary, and the different distances between the boundaries within a coating all affect such properties. The objective of the present work is to Design and Analysis the optical performance of HL- narrow (FWHM)band pass filter In mid infrared region (~3000–5000 nm) bases Transmitting Materials and calculate transmittance intensity for suggestion designs using computer program (Mat lab 10).

2- Theoretical Approach

Between incidence and exit media, which have respective refractive indices of Ninc and Nex, are a series of the thin layers of dj thickness and Nj refractive indices. The ith layer is represented by the following with the use of the characteristic matrix approach, which is extensively covered in the majority of optical coating textbooks, including Macleod [9].

$$M = \begin{pmatrix} M_{11} & M12 \\ M21 & M22 \end{pmatrix} = \prod_{j=q}^{j} M_j \text{.........(1)}$$

Where q represents number of the layers, and the product is taken in the reverse order due to the fact that upper layer matrices have to be multiplied on the left.

$$\begin{pmatrix} M11 & M12 \\ M21 & M22 \end{pmatrix} = \begin{pmatrix} \cos\delta_H & i\sin\delta_H / \eta_H \\ i\eta_H \sin\delta_H & \cos\delta_H \end{pmatrix} \begin{pmatrix} \cos\eta_L & i\sin\eta_L \\ i\eta_L \sin\eta_L & \cos\eta_L \end{pmatrix} ......(2)$$

δH & δL represent effective phase thickness, ηH & ηL represent effective optical admittance are the characteristic transfer matrices that are determined by characteristics of every one of the layers and incident electro-magnetic waves.

$(\delta j = 2\pi Nj\ dj \cos \vartheta_j / \lambda°$ …………(3)

Where j =H or L and ϑ_j represents angle of refraction in jth layer. The amplitude transmission coefficients of the multilayer are:

$$T = \frac{2\eta_{inc}}{\eta_{inc} m_{11} + \eta_{exi} m_{22} + \eta_{inc}\eta_{exi} m_{12} + m_{21}} ....(4)$$

$$T = \frac{\operatorname{Re} N_{exi}}{\operatorname{Re} N_{inc}} tt^*$$

$$T = \frac{\operatorname{Re} N_{exi}}{\operatorname{Re} N_{inc}} |tt|.^2 ....(5)$$

Eqution (4,5) shows T represents optical transmittance.
Where Re represents real part, *denotes the complex conjugate and T represents optical transmittance.

3- Materials and methods

The behavior of total multi-layer structure is estimated on the basis of individual layer characteristics in a stack when the optical filters designing, to become one of the possible candidates for multilayer configurations. In this article, HL Narrow FWHM Band Pass Filters are designing in the spectrum of MIR (3000-5000) nm, at wave-length design 4000nm, by using Mat lab software to transmit spectrum of interest selectively. It used four groups of materials: SiC/Si3N4, HgS/HfO2 CdS\ MgF2, and PbTe/CdTe, on a ZnSe substrate, where Si3N4, HfO2, MgF2, and CdTe, represent low refractive index (1.89), (1.87), (1.39) and (2.67) respectively, other materials in every one of the groups represent high refractive index SiC (2.55), HgS (2.67), CdS (2.31), PbTe (5.5) [16]. The choice of ZnSe substrate (n ~ 2.43) was driven by the good knowledge of this material due to its physical properties, it is an ideal substrate: it is a robust material with a negligible absorption coefficient in the wavelength IR range. It has a remarkably wide range of the transmission wave-length (0.45µm - 21.5µm). The open software tool

"Matlab" was utilized for designing interference optical filters. The characteristic matrix of thin film approach, which is used to compute the transmission properties of filters, could be used to express the optical characteristics of the filters and the polarization of electro-magnetic (EM) radiation state. Many multilayer filters are also designed using this software.

4-Results and Discussion

The most common narrow band-pass filter structure to reduce half width of pass band, ether utilize high order of n (increase the spacer thickness) or increase the reflecting surface reflectance. In this study The ratio of refractive indexes is controlled for groups of different materials for same suggestion design A / (HL)^2 (H2L) (2HL) (HL)(2HL) (HL)^4H / S at normal incidence, then the optical performance and half width of the designs are evaluated by changing that parameter. The first group consists from (SiC) as high refractive index and (Si3N4) as low refractive index with ratio of nH/nL (1.34) as shown in figure 1. The transmission spectra with bandwidth is very wide (52nm) and the transmittance recorded 98.6% at the reference wavelength (λ0 = 4000) nm.

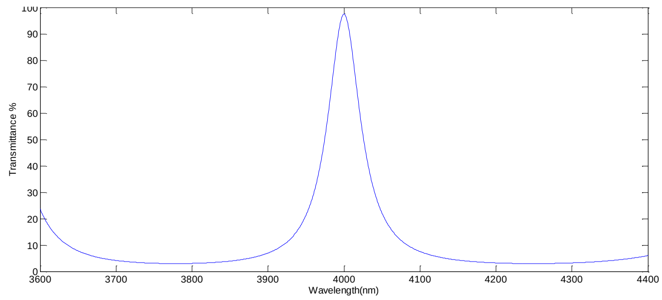

Figure -1 Transmission vs. wavelength for design SiC/Si3N4 at reference wavelength (λ0) 4000nm.

Figure (2) shows optical Transmittance of faction of wave length for second suggestion design of group which consist from(HgS) as the high refractive index and (HfO2) as low refractive index. From this figure shows when the ratio of refractive indices nH/nL are increases to (1.43), the transmittance increases to 99.3% and the (FWHM) decreases to 22 nm.

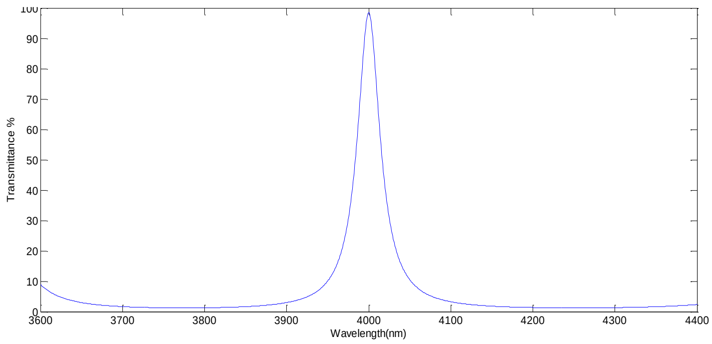

Figure- 2 Transmission vs. wavelength for design HgS/HfO2 at the reference wavelength (λ0) 4000nm

Figures 3 shows the transmission spectra of thierd design which consists from(CdS) as the high refractive index and (MgF2) as low refractive index by ratio in refractive indices for CdS/MgF2 is 1.66,where the maximum transmittance at the reference wavelength (λ0) 4000 nm is 99.13% while FWHM (4nm). The narrowband characteristic of filter design can be enhanced with the increase of retio of refractive index.

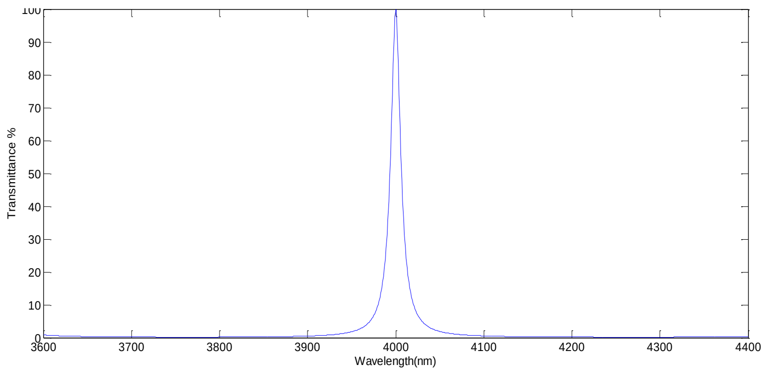

Figure -3 Transmission spectrum of CdS/MgF2 at 4000nm

Figure 4 presents the numerical simulation for transmittance spectra of forth design involve (pbTe) as the high refractive index and (HfO2) as low refractive with ratio in refractive indices for pbTe/HfO2 is 2.05. It can be observed that the transmittance dip (Tmax.) to about 93%, and Ultra-Narrowband with half-power bandwidth may be less than 2nm at the reference wavelength (λ0) 4000nm. This types of filters showing both thermally stable spectral properties and robust environmental durability characteristics for Plasma Spectroscopy, Differential Absorption Lidar (DIAL) and Deep-Space Optical Telecommunications appliction.

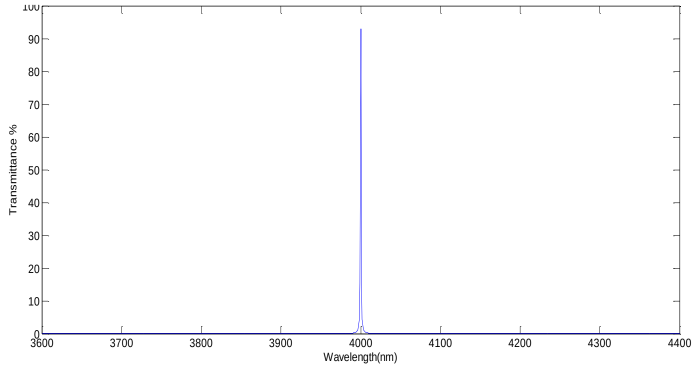

Figure- 4 Transmission spectrum of pbTe/CdTe at 4000nm

From the results obtained from numerical simulation from above figures we confine the suggested designs wide and narrow band pass filter depending on FWHM, in Comparison between four groups designs of different materials as shown in figure 5.

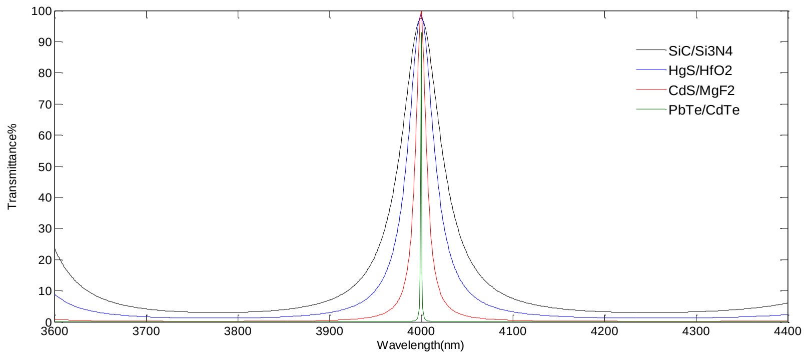

Figure- 5 Comparison between the FWHM for the four Suggestion designs.

One can conclude some result from figure 5 and arrange it in the table 1. In this table the results are listed for band-pass filters with ratios at different refractive indices which were designed by alternating multi-layer dielectric films to meet the requirements of high transmittance and narrow bandwidth. Also as shown in table 1 when the ratio of refractive indices increases the transmittance decreases and the Full width at half maximum (FWHM) decreases.

Table 1- Suggestion designs of four different band pass filters in Mid Infrared.

Material	Stack of design	Reflective index	NH/NL	No. Layers	FWHM (nm)	T% at (4000nm)
SiC/Si3N4	(HL)^2(H2L) (2HL)(HL)(2HL) (HL)^4 H	2.55/1.89	1.34	21	52	98.6
HgS/HfO2		2.67/1.87	1.43		22	99.3
CdS/MgF2		2.3/1.39	1.66		4	99. 13
PbTe/CdTe		5.5/2.67	2.05		2	92.98

Figures (6),(7) show the FWHM and optical transmittance as function of ratios at different refractive indices for the four Suggestion designs of groups designs of different materials. These figures display that, the ratio of the high refractive index layer to low refractive index layer (nH/nL) is inversely proportional to the transmittance and the band pass filter width. The material of band pass filter (HgS/HfO2) is given the best transmittance about 99.3% and then the transmittance of the material (CdTe/MgF2) is 99.13%.

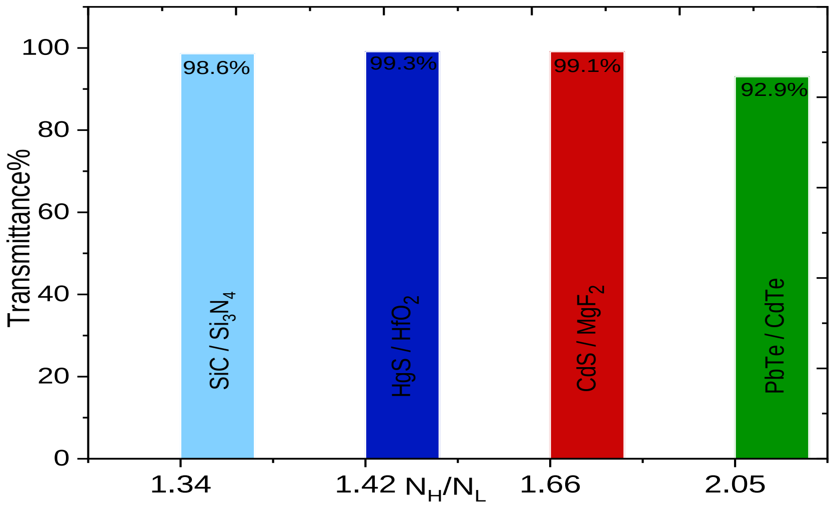

Figure- 6 The optical transmittance of four different band pass filters in Mid Infrared.

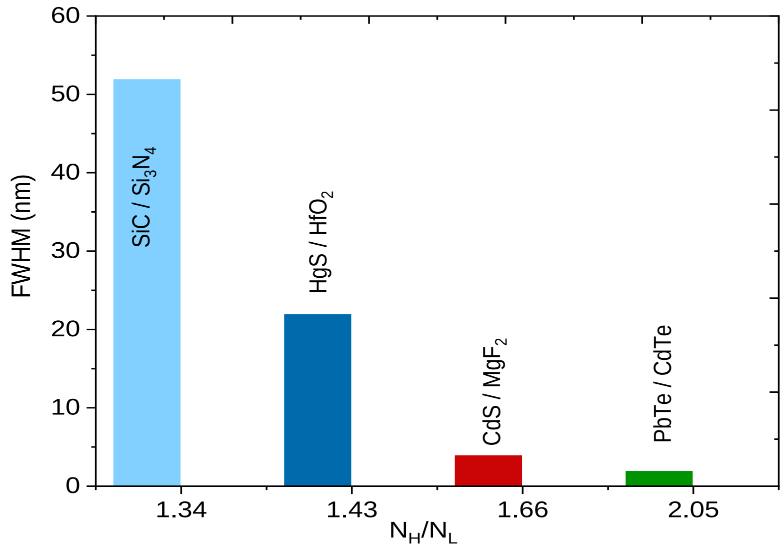

Figure- 7 The FWHM of four different band pass filters in Mid Infrared.

Figure 7 shows that the ratio of the high refractive index to low refractive index (nH/nL) is inversely proportional to the width of band pass filter. The material of band pass filter (SiC/Si3N4) is given the best results as shown in Fig.6 & Fig.7.

5-Conclusion:

In conclusion, results were presented for the development of narrow band pass in mid infrared region. Theoretically design of a narrow band pass filters by using optical materials: (PbTe), (CdS), (HgS),(SiC) and (CdTe), (MgF2), (HfO2),(Si3N4) as a high and low refractive index respectively to coated ZnSe as a substrate. The results shows that, the transmittance about (92%-99%) for the design (A / (HL)^2(H2L)(2HL)(HL)(2HL)(HL)^4H /S). One can conclude that the Band pass filter width display changes with refractive index ratio. The ratio of high refractive index to low refractive index is inversely proportional to the transmittance and width of band pass filter. This mean, the optical transmittance and width of band pass filter may be regulated by varying the ratio of high refractive index layer to low refractive index layer.

Conflict of interest: I declare that there is no conflict of interest with any governmental or research entity

.

References

1] B. Baloukas and L. Martinu, “Optical Thin Films and Coatings,” Opt. Thin Film. Coatings, no. June 2018, pp. 631–663, 2013, [Online]. Available: http://www.sciencedirect.com/science/article/pii/B978085709594750017X

[2] H. Tang, J. Gao, J. Zhang, X. Wang, and X. Fu, “Preparation and spectrum characterization of a high quality linear variable filter,” Coatings, , 2018, vol. 8, no. 9, pp. 1–11 doi: 10.3390/COATINGS8090308.

[3] YAREMCHUK, I.; FITIO, V.; BOBITSKI, Ya. New design of interference band-pass infrared filter. Opto-Electronics Review, 2011, 19.2: 193-197.

[4] S. Türker-Kaya and C. W. Huck, “A review of mid-infrared and near-infrared imaging: Principles, concepts and applications in plant tissue analysis,” Molecules, 2017, vol. 22, no. 1,doi: 10.3390/molecules22010168.

[5] Y. Kanamori, M. Shimono, and K. Hane, “Fabrication of transmission color filters using silicon subwavelength gratings on quartz substrates,” IEEE Photonics Technol. Lett., 2006, vol. 18, no. 20, pp. 2126–2128doi: 10.1109/LPT.2006.883208.

[6] S. P. Mahulikar, H. R. Sonawane, and G. Arvind Rao, “Infrared signature studies of aerospace vehicles,” Prog. Aerosp. Sci., 2007, vol. 43, no. 7–8, pp. 218–245,doi: 10.1016/j.paerosci.2007.06.002.

[7] J. E. Rhoads, S. Malhotra, P. Scowen, R. Probst, and D. McCarthy, “Multiband filters for near-infrared astronomical applications,” Ground-based Airborne Instrum. Astron. III, 2010 ,vol. 7735, no. July 2010, p. 77356C, , doi: 10.1117/12.856737.

[8] M. H. Asghar, M. Shoaib, F. Placido, and S. Naseem, “Wide bandpass optical filters with TiO2 and Ta2 O5,” Cent. Eur. J. Phys., 2008,vol. 6, no. 4, pp. 853–863, doi: 10.2478/s11534-008-0104-3.

[9] H. A. Macleod, Thin-film optical filters, 5rd edition, Ed.W.T., Institute of physics publishing, Welford,(2007), doi:https://doi.org/10.1201/9781420033236

[10] G. H. Abdullah, B. R. Mahdi, and G. Farah, “Design and analysis Narrowband filters,” 2013,vol. 4, no. 8, pp. 1854–1862,.

[11] S. I. Awaad, “Design and improvement high pass filters for microwave region,” J. Al-Anbar Univ. Pure Sci. , 2015,vol. 9, no. 2, pp. 43–47, [Online]. Available: https://www.researchgate.net/publication/303921075_Design_and_improvement_high_pass_filters_for_microwave_region

[12] S. N. Turki and M. April, “Optimization Design of Band Pass Filter in The Infrared Region,” Int. J. Emerg. Trends Technol. Comput. Sci., 2015, vol. 4, no. 2, pp. 2–6, [Online]. Available: http://www.ijettcs.org/Volume4Issue2/IJETTCS-2015-03-01-3.pdf

[13] U. Brauneck, R. Sprengard, S. Bourquin, and A. Marín-Franch, “Dense grid of narrow bandpass filters for the JST/T250 telescope: summary of results,” J. Astron. Telesc. Instruments, Syst., 2018,vol. 4, no. 01, p. 1, doi: 10.1117/1.jatis.4.1.015003.

[14] S. Song, F. Sun, Q. Chen, and Y. Zhang, “Narrow-linewidth and high-transmission terahertz bandpass filtering by metallic gratings,” IEEE Trans. Terahertz Sci. Technol., 2015,vol. 5, no. 1, pp. 131–136, doi: 10.1109/TTHZ.2014.2365679.

[15] AMOTCHKINA, Tatiana, et al. Advanced thin-film software techniques improves design-to-fabrication workflow. Laser Focus World, 2015, 51.1: 87-90.

[16] DUTTA, Mintu Maan; GOSWAMI, Mridusmita. Coating Materials: Nano-Materials. In: Advanced Surface Coating Techniques for Modern Industrial Applications. IGI Global, 2021. p. 1-30.