New Designs of Multiple-Cavity Optical Filters for Infrared Applications

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Abstract

Designing multi-cavity interference filters that combine a narrow bandpass with a flat-top shape is sophisticated as it requires difficult computer techniques and non-quarter wave stacks. This work proposes theoretical designs of three and four cavities of narrow bandpass optical filters. Tantalum pentoxide (Ta_2O_5) and silicon dioxide (SiO_2) were used as high- and low-index materials, respectively, and fused silica for the substrate material. The transmittance spectra of these designs were plotted in MATLAB. The designs are straightforward and use an all-quarter-wave multilayer stack. All designs exhibited nearly ideal flat-top profiles, narrow bandwidths (3–6 nm), and transmittances of 0.93–0.95% in the IR range (1550 nm). These reliable designs are efficient for desirable applications in the infrared range.

Keywords: Flat-top Profiles, Narrow Band-pass Filters and Optical Interference Filters.

تصاميم جديدة للمرشحات البصرية متعددة التجاويف لتطبيقات الأشعة تحت الحمراء

حسام صبيح العرب

هيئة البحث العلمي / مركز بحوث وتكنولوجيا البيئة والمياه والطاقات المتجددة – بغداد – العراق

الخلاصة

إن تصميم مرشحات التداخل متعددة التجاويف التي تجمع بين تمرير نطاق ضيق وشكل ذو قمة مسطحة هو أمر معقد لأنه يتطلب تقنيات حاسوبية صعبة، واستخدام حزم موجية ليست من نوع الربع موجة. يقترح هذا العمل تصاميم نظرية لثلاثة وأربعة تجاويف للمرشحات الضوئية التي تسمح بتمرير نطاق ضيق. تم استخدام خامس أوكسيد التنتاليوم (Ta_2O_5) وثاني أوكسيد السيليكون (SiO_2) كمواد عالية وواطئة الانكسار على التوالي، والسيليكا المنصهرة كمادة للطبقة الأساس . تم رسم أطياف النفاذية لهذه التصاميم بواسطة برنامج MATLAB. هذه التصاميم سهلة وتستخدم مجموعة متعددة الطبقات ذات الربع موجة. أظهرت جميع التصاميم أشكالًا ذات قمم مسطحة مثالية تقريبًا، ونطاقات ضيقة (٣ – ٦ نانومتر)، ونفاذية (٠.٩٣ – ٠.٩٥ ٪) في مدى الأشعة تحت الحمراء (١٥٥٠ نانومتر). تعتبر هذه التصاميم فعالة للتطبيقات المرغوبة في نطاق الأشعة تحت الحمراء.

الكلمات المفتاحية: أشكالًا ذات قمم مسطحة، مرشحات تمرير النطاق الضيق ومرشحات التداخل البصري.

Introduction

In recent years, optical thin films have attracted increasing attention as a core technology for many tools such as reflectors, polarizers, and pass-band filters. These filters have numerous purposes in Raman spectroscopy and infrared (IR) applications (Cai, *et al*., 2011; Mohammad, *et al*., 2016; Lu, 2009; Guembe, *et al*., 2017; Stolberg-Rohr and Hawkins, 2015), telecommunications (Vázquez, *et al*., 2015; Willey, 2008; Ghasemi, 2013), Switchable and tunable fiber laser (Qin, *et al*., 2021), absorbing short-wave filters (Bembenek, *et al*., 2022), astronomical studies and space applications (Hawkins, *et al*., 2008; Begou, *et al*., 2017; Rahmlow, *et al*., 2018), fluorescence imaging microscopy (Butt, *et al*., 2016$_a$; Favreau, *et al*., 2014; Butt, *et al*., 2016$_b$) and spectroscopic equipment (Habib and Ullah, 2016).

Bandpass filters can be designed using various methods. Some of these methods use overlap between the pass regions, (Rancourt, 1996; Thelen, 1989; Baumeister, 2003; Macleod 2017) and this usually occurs when the materials are made of all-dielectric short (SWP) and long (LWP) wavelength pass filters. Another method is using a metal-dielectric combination where the mirrors are thin metal layers and the spacer is an all-dielectric layer (Thelen, 1989; Macleod, 2017). However, this latter method is still causing a problem of low transmittance due to absorption losses in the metal layers. Narrow band-pass filters, or multi-cavity interference filters, resemble solid Fabry-Perot filters, yet the shape (Profile) of the passband is far different. These filters have squarer (Flat) tops to their transmission band, therefore allowing more energy in the passband through the filter (Rancourt, 1996).

It can be seen from the previous studies that a nearly flat top transmittance peak with sharp rise and fall could be obtained when some layers in the coupling reflector stacks are non-quarter wave thick (Thelen, 1989; Baumeister, 2003). Nevertheless, the major filter characteristics can be achieved with all-quarter-wave multilayer stacks; the present study has been restricted to such stacks. In addition, one of the main problems in designing narrow band-pass filters is the “rabbit’s ears" on both sides of the passband. This could be worse with rising numbers of stack periods (Macleod, 2017).

The first computer technique developed by Baumeister in 1958 (Philip Baumeister, 1958) regarding optical coating design explained the possibility of optimizing optical filters using a computer program. Although more complex designs and high-level numerical processes followed this technique, it is highly complicated to design a filter for a specific purpose without an optimization via refinement (Baumeister, 1958; Larouche and Martinu, 2008). There are many refinement techniques, like damped least squares, linear search techniques, flip-flop optimization, statistical testing methods, differential evolution, gradual evolution, needle variation methods, and others (Macleod, 2017). A systematic approach for designing narrow bandpass filters does not currently exist. The method of trial and error, supported by precise computer calculations, is commonly used.

The design process primarily involves trial and error, often involving the replacement of unattainable or hard indices with symmetrical combinations of optimum materials. The design is then improved to accommodate the dispersion of optical constants in real materials and to compensate for the apparent dispersion that happens when coupled with symmetrical periods (Macleod, 2017).

Telecommunication applications often necessitate the use of narrowband-pass filters, which may include designs consisting of over 100 individual layers and, in some cases, exceeding 200 layers (Macleod, 2017). The literature clearly demonstrates that developing a filter is a complex task.

Due to the difficulties and complexities involved, this work will offer new theoretical designs for multi-cavity narrowband optical filters that use the least number of layers—based on trial and error—of the standard periodic quarter-wave stack. This approach is expected to be a conventional and straightforward method for designing multi-cavity filters. Furthermore, there is a significant level of skill involved in using the trial and error method with the periodic quarter-wave structure to create a filter with a specific spectral bandwidth (Baumeister, 2004). The results of this work will facilitate the development of optical filters that have narrow bandwidths and nearly perfect flat-top shapes.

Materials and Methods

Narrow bandpass optical filters need to have very steep cut-on and cut-off transmittance properties, as well as very low transmittance at wavelengths outside the wanted range (The Transmission Wavelength), in order to get the required characteristics. The simplest type of these is the famous Fabry-Perot filter, which has a triangular passband shape; it is possible to improve this by combining simple filters in series in the same way as tuned circuits. These combined assemblies are identified as multi-cavity optical filters or multiple half-wave optical filters. All mathematical equations ruling the interface of electromagnetic waves with optical thin films are detailed by (Thelen, 1989) and (Macleod, 2017), and others. These equations permit the reflectance estimation of a single film or a multiple film stack on a substrate. In this research, the optical admittance method is applied to calculate the interaction of light (Infrared Waves) with high and low refractive indices thin films. A short brief of these equations is given here, along with a related diagram, Figure (1). Mj is a 2×2 matrix which represents the j th film of the system: (Bass, 2010; Macleod, 2017):

$$\begin{bmatrix} cos\delta_j & isin\delta_j/\eta_j \\ isin\delta_j\eta_j & cos\delta_j \end{bmatrix} \ldots\ldots\ldots\ldots\ldots.. (1)$$

Where

$$\delta_j = 2\pi(\eta_j\, d_j\, cos\theta_j)/\lambda \ldots\ldots\ldots\ldots\ldots (2)$$

The quantity (nj dj cos θj) is the effective optical thickness of the layer j for an angle of refraction θj. η represents the effective refractive index of the medium, substrate, or layer. The angles are measured from the surface normal (θ = 0). All other quantities and equations are expressed regardless of polarization.

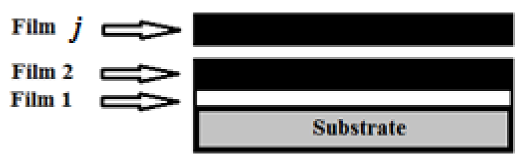

Figure (1) Multilayer Thin Film Stack Diagram. Each Layer of The Optical Thin Film has its Own Specific Admittance, as Given by Eq. (1).

The optical admittance of a thin film stack (Y) is the product of the admittances of individual layers (Bass, 2010).

Y = [Thin film j]*...*[Thin film 1]*[Substrate] (3)

The reflectance is given by (Macleod, 2017):

$R=(Y_o-Y/Y_o+Y)*(Y_o-Y/Y_o+Y)$ (4)

Y_o is the admittance of air. The mentioned equations are adequate to measure reflectance in the case of optical properties, and the individual layer thicknesses are identified for all applicable wavelengths.

Results and Discussion

Design Materials

Many materials can be suitable for use in the IR region at 1550 nm. Depending on the refractive indices and absorption coefficients of the coating materials, tantalum pentoxide (Ta_2O_5) is chosen for its high refractive index (nH=2) layer (H), whereas silicon dioxide (SiO_2) is selected for its low refractive index (nL=1.46) layer (L). Fused silica is used as the substrate material (n=1.444) layer (S). All these materials have very low absorption for the selected central wavelength (Cai, *et al*., 2011; Ghasemi, 2013; Macleod, 2017).

The suggested filter designs

Determining how many layers to use is never simple. Fortunately, with a fairly fast computer, a little trial and error is a totally reasonable and straightforward method. During the design phase, we make the matching assemblies on each side of the filter's core, which we will retain as a sequence of quarter-waves. This matching assembly will significantly lessen the steepness of the edge. The processes of constructive and destructive interference that arise between reflections from different layers will determine the transmittance (T%) of the filter depending on the number and thickness of dielectric layers and the angle of incident light on the filter. The proposed designs are shown in Table (1). Figure (2 and 3) show the transmittance versus wavelength of the two suggested designs; each one has two types of cavities, 3 and 4. The full width at the half-maximum (FWHM) is an important parameter of optical filter performance that has been calculated using mathematical and computational methods.

Table (1) Suggested Designs of Narrow Band Pass Filters.

Filter Design	No. of Cavities	Filter Structure
1st	3	$(HL)^5(HH)^2(LH)^5L(HL)^5(HH)^8(LH)^5L(HL)^5(HH)^2(LH)^5$ S
	4	$(HL)^5(HH)^2(LH)^5L(HL)^5(HH)^8(LH)^5L(HL)^5(HH)^8(LH)^5L(HL)^5(HH)^2(LH)^5$ S
2nd	3	$(HL)^6(HH)(LH)^6L(HL)^6(HH)^8(LH)^6L(HL)^6(HH)(LH)^6$ S
	4	$(HL)^6(HH)(LH)^7L(HL)^6(HH)^6(LH)^7L(HL)^6(HH)^6(LH)^7L(HL)^6(HH)(LH)^6$ S

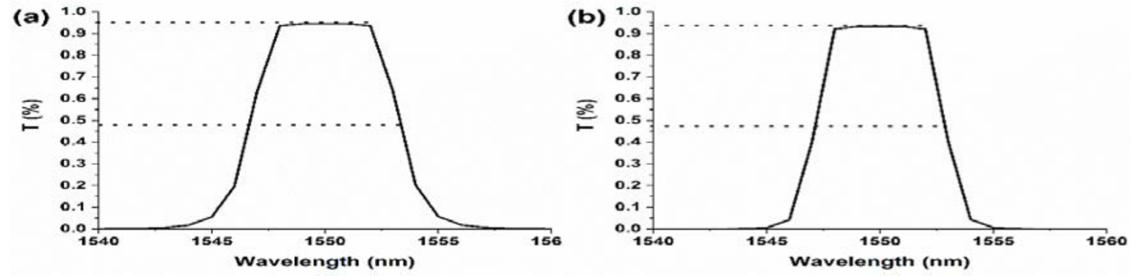

Figure (2) First Suggested Designs: (a) 3 Cavities, (b) 4 Cavities.

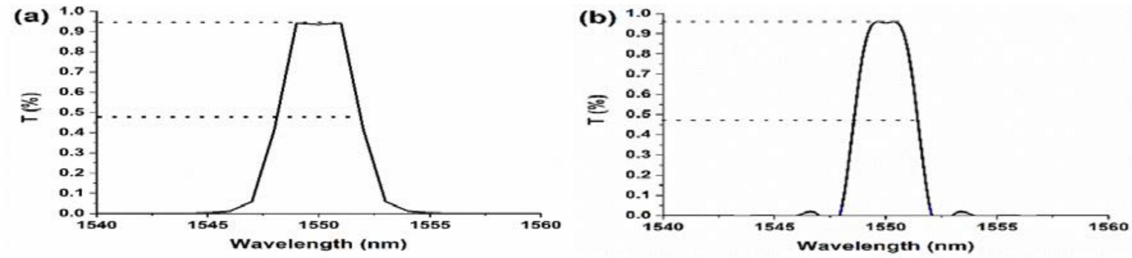

Figure (3) Second Suggested Designs: (a) 3 Cavities, (b) 4 Cavities.

Table (2) Optical Characteristics of The Suggested Designs.

Filter Design	No. of Cavities	FWHM [nm]	T [%]	Order of Cavities
1st	3	6	0.95	2-8-2
	4	5	0.93	2-8-8-2
2nd	3	3.8	0.94	1-8-1
	4	3	0.95	1-6-6-1

Table (3) Comparison of Some Characteristics of The Present Suggested Designs with Previous Results of Narrow Bandpass Filters.

FWHM (nm)	T [%]	Reference
3 - 6	0.93 - 0.95	This work
≈ 10	> 80	[1]
4.2 – 17.5	≈ 100	[4]
4 - 10	80	[8]

It is clear that the FWHM decreases with increasing the number of layers and the number of spacers. Meanwhile, the transmittance (T%) is slightly decreased in the first (1^{st}) design and increased in the second (2^{nd}) design. The results obtained from these figures are summarized in Table (2). The spectral profiles of the proposed designs are performed using equations 1–4 and the MATLAB programming language. The programming steps are presented in a flowchart as shown in Figure (4).

The calculated (FWHM) and (T%) values were found to be around 3–6 nm and 93–95%, respectively, which are comparatively either corresponding with or better than the same obtained values for other previous narrow bandpass filters (Cai, *et al*., 2011; Stolberg-Rohr and Hawkins, 2015; Hawkins, *et al*., 2008) as summarized in Table (3).

The results listed in Tables (2) and (3) show that there is agreement between the characteristics of the proposed designs and the results of other previous studies (Cai, *et al*., 2011; Stolberg-Rohr and Hawkins, 2015; (Hawkins *et al*., 2008), and this reveals the possibility of using these proposed designs in different fields within the IR range, such as Raman applications and other space applications.

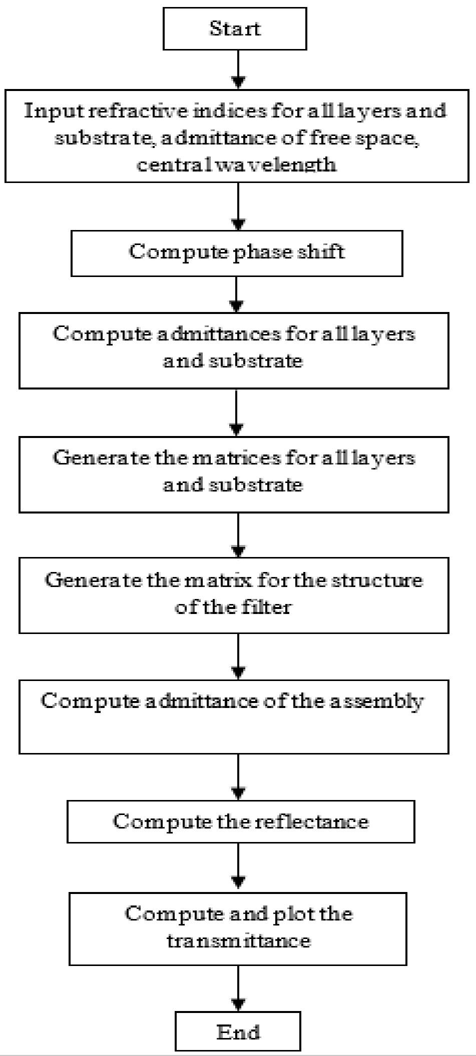

Figure (4) The Flowchart of The MATLAB Processes for Simulating the Suggested Design Profiles.

Conclusions

The objective of this study was to introduce novel designs of interference filters with multiple cavities using a straightforward approach. The suggested designs demonstrated favorable characteristics, including narrow bandwidths, high transmittance, and almost perfect flat-top forms. The results also showed that these specific optical filters, which are made to work in the infrared (IR) range, could be used effectively in a number of different areas within this range, such as optoelectronics and electronic devices.

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