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Designing bandpass filters in 8 – 14 μm range for Si and Ge substrates

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Abstract. Modular bandpass spectral filter for germanium and silicon substrates in 8 – 14 μm band applications have been proposed. The design approach, similar to antireflection coating design has been adopted to make the model simple with lesser number of layers. The full width half maximum (FWHM) value of the filter for the two substrates is varied by varying the refractive index of a single layer in the multilayer stack. The design is also analyzed for zero and 45 degree angles of incidence. The analysis has shown that the designed configuration exhibits identical behavior for these two substrates. The proposed configuration could be used for different optical and optoelectronic applications.

Keywords: multilayer, full width half maximum (FWHM), transmittance.

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1. Introduction

Any interference filter is known to be a certain multilayer system consisting of the consequently deposited layers made of materials with different refractive indices [1-5]. Most often, only two alternating layers from film-making materials are involved. In the case of narrow-band filters, the optical thickness of the multilayer system (Fabry – Perot filters) [1] or of several non-adjacent layers (multihalf-wave filters) [3, 4] is multiple of $\lambda_0/4$, whereas that λ_0 is the wavelength of the peak transmittance of the Fabry – Perot filter or, in the case of multihalf-wave filter, the wavelength of the transmittance band (or bands) center. The cut-off shortwave and longwave filters contain no half-wave layers, while the optical thickness of their outer layers made of the same materials usually equals $\lambda_0/8$, where λ_0 is the wavelength of the high reflection band center. To obtain the more smoothed spectral characteristics of the cut-off filters, the optical thickness of some layers is made different from the quarter-wavelength one. The number and position of such layers are determined by various optimization procedures [2, 5]. The disadvantage common to the multilayer systems (not only to the filters) is their comparatively narrow high transmittance and high-reflection bands. For example, in the case of two-component interface filters, the short-wavelength λ_S and the long-wavelength λ_L background suppression region coincide with the edges of the first zone of high reflection from a multilayer stack formed by a succession of alternating layers made of materials with the high (n_H) and low (n_L) refractive indices and the optical thickness $\lambda_0/4$. The conventional well-known expressions for the filters based on two materials are given as in [2]: $\lambda_{L,S} = \lambda_0 \pm \Delta\lambda_{L,S}$,
where $\lambda_{L,S} = \lambda_0\, \Delta[\lambda_0 / \lambda]/[1 \mp \Delta(\lambda_0 / \lambda)]$
and $\Delta(\lambda_0/\lambda) = 2/\pi \sin^{-1}[(n_H - n_L)/(n_H + n_L)]$.

When the optical thickness deviates from the quarter wavelength one, while keeping the half-wavelength thickness of the repeated periods $\Delta\lambda$ decreases [6, 7].

In this paper, we have proposed a modular thin film multilayer structure to be used as a band pass filter in 8 to 14 μm region, for different substrate materials. The approach used to design such a filter is different from the standard methods described by the above-mentioned expression. Antireflection coating design approach has been used to design the modular structure for band pass application [8-12]. The multilayer configuration has been optimized by varying the thickness and refractive indices of the layers.

2. Theory of multilayer matrix calculations

The matrix method for calculating spectral coefficients of the layered media was first suggested by F. Abeles (1950) and has been widely employed ever since [13]. Matrix calculations determine the spectral transmittance and reflectance profile for multilayer structures on a substrate. Consider a loss free multilayer design, normally incident radiations, and assume that films are optically homogenous. The electric field (E_{m-1}) and the magnetic field (H_{m-1}) at the incident boundary of a film are related to the electric field vector E_m and magnetic field vector H_m vectors at the boundary of the adjacent film by the product of the following matrices per layer. The matrix is calculated at each boundary throughout the multilayer as the magnitude of electric and magnetic field vectors alter with the layer properties [14]. Application of the appropriate boundary conditions between each layer requires that the tangential components of E and H vectors are continuous across each boundary to the equations of wave propagation.

Let the electric and magnetic field vectors of the wave traveling in the direction of the incidence are denoted by the symbol "+", and those waves traveling in the opposite direction by the symbol "–". At the interface of m^{-th} layer, the tangential components of E and H are given as

$E_m = E_m^{\ +} + E_m^{\ -}$,

$H_m / H_1 = E_m / E_1$,

$$H_m = E_m \cdot H_1 / E_1. \tag{1}$$

Neglecting the common phase factors, and where E_m and H_m represent the resultants then:

$$E_m^{\ +} = 1/2\left[\frac{H_m}{H_1 / E_1} + E_m\right], \tag{2}$$

$$E_m^{\ -} = 1/2\left[-\frac{H_m}{H_1 / E_1} + E_m\right], \tag{3}$$

$$H_m^{\ +} = 1/2\left[H_m + \frac{E_m H_1}{E_1}\right], \tag{4}$$

$$H_m^{\ -} = 1/2\left[H_m - \frac{E_m H_1}{E_1}\right]. \tag{5}$$

The fields at other interfaces m–1 are similar to equations 2-5 at the same instant of time and a position with identical x and y coordinates. These can be determined by multiplying by the phase difference in z direction given by $e^{i\delta}$ or $e^{-i\delta}$ where

$$\delta = \frac{2\pi N_1 d \cos\theta_1}{\lambda} \tag{6}$$

and θ_1 may be complex. The values of E and H at this interface are therefore

$$E^+_{\ m-1} = E^+_{\ m} e^{i\delta} = 1/2\left[\frac{H_m}{\eta_1} + E_m\right]e^{i\delta}, \tag{7}$$

$$H^+_{\ m-1} = H^+_{\ m} e^{i\delta} = 1/2\left[H_m + \eta_1 E_m\right]e^{i\delta}, \tag{9}$$

$$H^-_{\ m-1} = H^-_{\ m} e^{-i\delta} = 1/2\left[H_m - \eta_1 E_m\right]e^{-i\delta}, \tag{10}$$

where η_1 is the tilted optical admittance given by $\eta_1 = H_1/E_1$. Now

$$E_{m-1} = E^+_{m-1} + E^-_{m-1}$$

$$E_{m-1} = E_m \cos\delta + H_m \frac{i\sin\delta}{\eta_1}, \tag{11}$$

$$H_{m-1} = E_m \frac{i\sin\delta}{\eta_1} + H_m \cos\delta, \tag{12}$$

This can be written in matrix form as

$$\begin{bmatrix} E_{m-1} \\ H_{m-1} \end{bmatrix} = \begin{bmatrix} \cos\delta & (i\sin\delta)/\eta_1 \\ i\eta_1 \sin\delta & \cos\delta \end{bmatrix} \begin{bmatrix} E_m \\ H_m \end{bmatrix}. \tag{13}$$

Solving the above given expression [15], the matrix expression for single layer is:

$$M_1 = \begin{bmatrix} A & iB \\ iC & D \end{bmatrix} \tag{14}$$

where $\cos\delta_m = A = D$, $i\sin\delta_m / \eta_m = B$, $i\sin\delta_m \eta_m = C$. Similarly as [16] for a multilayer containing q-layers can be given as

$$\begin{bmatrix} E_O \\ H_O \end{bmatrix} = \prod_{m=1}^{q} M_m \begin{bmatrix} E_q \\ H_q \end{bmatrix}. \tag{18}$$

The loss-free transmittance and reflectance for the multilayer assembly can be calculated from this product matrix by

$$T_q = \frac{4 n_s n_o}{(n_o AA + n_s DD)^2 + (n_o n_s BB + CC)^2}, \tag{19}$$

$$R_q = \frac{(n_o AA - n_s DD)^2 + (n_o n_s BB - CC)^2}{(n_o AA + n_s DD)^2 + (n_o n_s BB + CC)^2}. \tag{20}$$

The reflectance, transmittance and absorbance are then related by $R + T + A = 1$. The solution of this matrix theory is a laborious job for multilayer coatings. Based on the matrix theory, we have developed a software program to design and simulate the performance of multilayer coatings and filters [17].

3. Design and analysis

A simple approach to design a modular multilayer structure comprising quarter and half-wave thick layers at a design wavelength of 10.5 μm, similar to that of designing antireflection coatings has been used. This approach has been adopted to make the number of layers as less as possible compared to the standard design procedures involving a large number of layers repeated periodically, with an acceptable output performance and easy manufacturing process. Substantial growth of number of layer is not so desirable because of the more complicated process of fabrication of coatings [18].

The proposed multilayer configuration could be used for two different substrates, as in our case of Ge and Si. These substrates are optically transparent in 8 – 14 μm but exhibit very high reflection in the said region. These materials are also common optical material in above

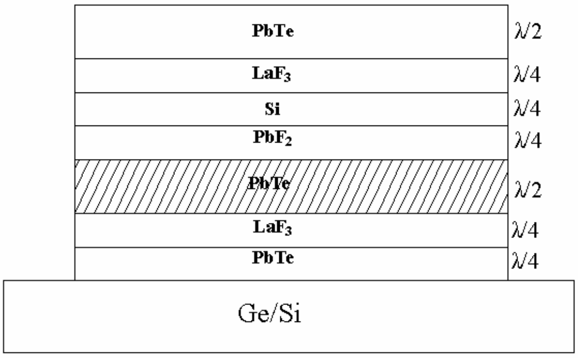


Fig. 1. Basic model configuration of multilayer bandpass filter.

mentioned wavelength band [19]. The basic multilayer configuration is given in Fig. 1, and the composition of multilayer stacks is given in Table. The filtering effect could be seen in the band from 9.75 to 11.5 μm.

Fig. 2 (a-b) shows the transmittance of the filter for germanium substrate at two different angles of incidence. It is well seen that the difference in transmittance profiles of polarized and unpolarized radiation is not very significant for the higher angle. At 45º, the transmittance band shifts slightly towards short wavelength with a very small split in the *s* and *p* component of light. The magnitude of the shift is approximately 0.4 μm.

The width of the pass band is varied by a single layer in the stack. In this case, the layer number 5 as shown in Fig. 1 is used to vary the width of the passband. This is a half-wave thick layer comprising of PbTe with $n = 5.5$ (Table). For this material, the full width half maximum FWHM value is 0.899 μm. When this layer is replaced by Ge ($n = 4.0$) the FWHM maximum increases up to 1.06 μm with a slight broadening of the peak as well. Further reduction in the value of n to 3.42 (Si) makes the FWHM to 1.138, and the peak further broadens. Decreasing the refractive index below this value tends to decrease the transmittance and loss of the band shape. In this way, the width of the pass band can be varied within a specific range, which could be helpful in fine-tuning such filters. This effect is shown in Fig. 3.

Layer definition of multilayer stack model.

Sr. #	Layer Material & index	Thickness
1	PbTe (5.5)	λ/2
2	LaF_3 (1.4)	λ/4
3	Si (3.42)	λ/4
4	PbF_2 (1.73)	λ/4
5	PbTe (5.5)	λ/2
6	LaF_3 (1.4)	λ/4
7	PbTe (5.5)	λ/2
8	Substrate (Ge, Si)	Massive

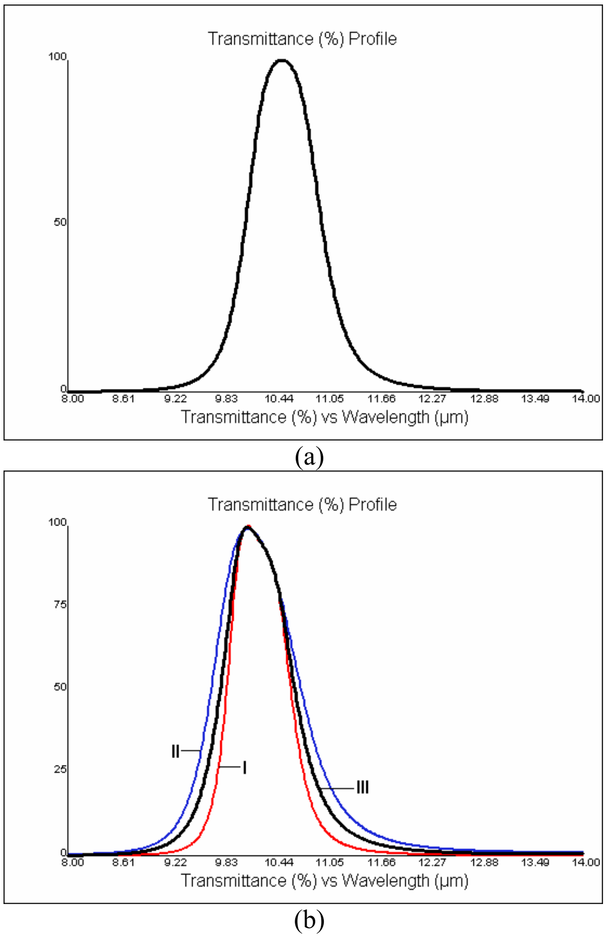


Fig. 2. Transmittance profile of the band pass filters on Ge substrate at (a) at normal incidence, (b) 45º, I: *s*-polarized, II: *p*-polarized, and III: unpolarized curves.

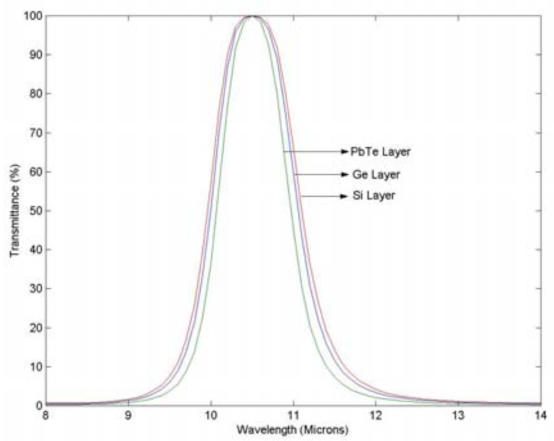
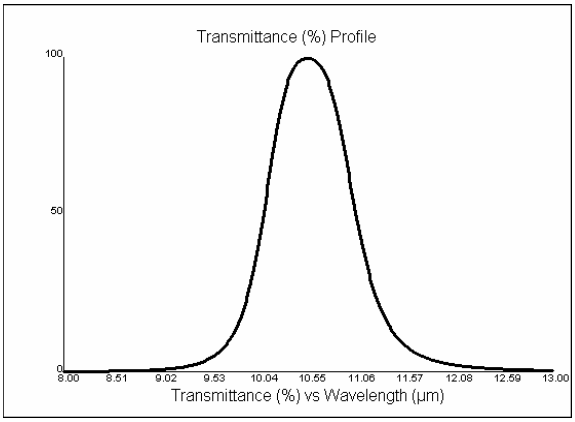
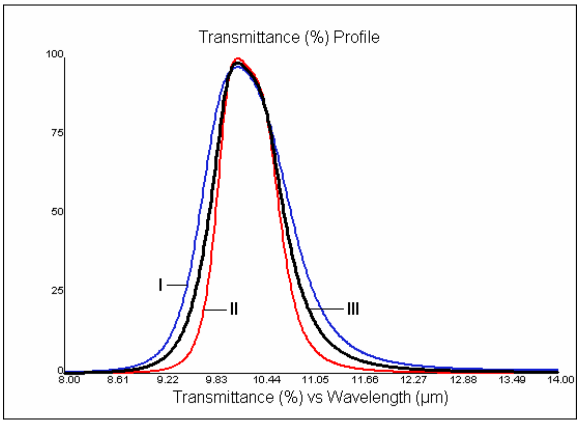


Fig. 3. Variation in FWHM with change in material of layer 5 on Ge substrate. with PbTe, Ge and Si layer

A similar multilayer model has been used for silicon substrate. Fig. 4 (a-b) shows the transmittance profile with 0 and 45º of the incidence angle. Very similar results are obtained for shifting the band to shorter wavelengths, with the peak transmittance very close to unity. Peak broadening is also prominent with variation of the refractive index of the layer # 5 for this substrate as well. The split of light into *s* and *p* components at $\theta = 45°$ is very small again. The magnitude of the peak shift at 45^o is again approximately 0.4 µm. The layer #5 is replaced first with germanium and then with silicon to vary FWHM of the passband. For basic configuration with PbTe, the FWHM value has been found to be 0.95 µm. When replaced with Ge layer, the width increases up to 1.11 µm, and it goes up to 1.20 µm with Si layer. This effect has been shown in Fig. 5. The variation in FWHM with variation in the layer #5 on both Ge and Si substrates is shown in Fig. 6. The same trend has been observed for these two substrates. FWHM is inversely proportional to the refractive index. However, FWHM has a greater magnitude for Si substrate as compared to Ge one. This has been attributed to the low refractive index of Si as compared to Ge.



(a)



(b)

Fig. 4. Transmittance profile of the bandpass filters on Si substrate at (a) normal incidence, (b) 45º, I: *s*-polarized, II: *p*-polarized, and III: unpolarized curves.

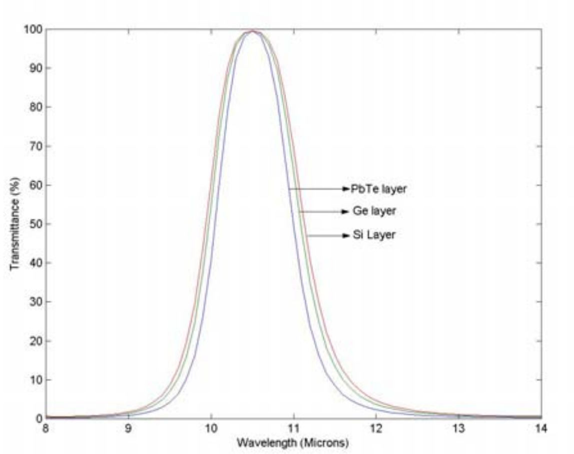


Fig. 5. Variation in FWHM with the change in material of layer 5 on Si substrate with PbTe, Ge and Si layer.

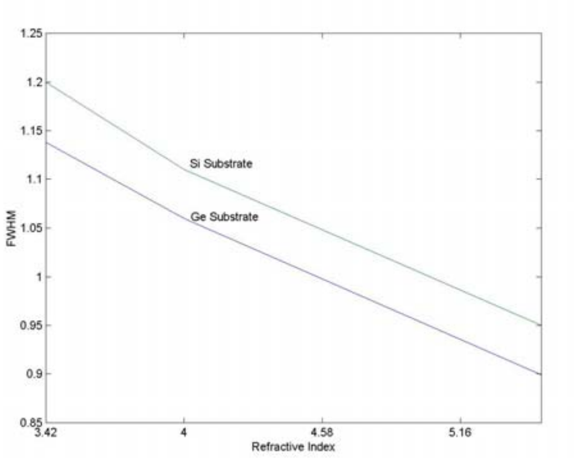


Fig. 6. Variation in FWHM with change in material of layer 5 on Si & Ge substrates.

4. Conclusions

Modular filter design approach is a useful technique to design single configuration spectral filters for more than one substrate materials. The spectral filter given in this paper is based on the same approach. This filter has been analyzed for its performance, and has been found to exhibit stable and reasonable performance for Si and Ge substrates. Further, it contains very fewer layers as compared to conventional two material symmetric period filter designs. Moreover, the variation in FWHM with the change in refractive index material for the layer #5 provides an easy way to fine tune the filter. It is expected that this approach would prove to be useful in designing modular optical coatings for future applications.

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