ULTRA-NARROW BANDPASS INTERFERENCE FILTER FOR INFRARED APPLICATION

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ABSTRACT

In this work, a theoretical designs of ultra-narrow bandpassfilter to operate in the infrared region (i. e. for laser CO_2) is proposed, in order to detect spectral lines with full width at half maximum (FWHM) is less than 2 nm. This filter is constructed by coat substrate by two transparent coating material with high and low refractive index. The effect of incidence angle of the electromagnetic on the filter also studied. The results shows that, for normal incidence, high transmittance (T > 98 %) at the center of design wavelength(λ_o) with very lowtransmittance in the rejection region. As the angle of incidence increase, the transmittance decreases as a result of varying in thickness of the layers.

Keywords: Band-pass filters, Multilayer Optical Coating, Fabry-Perot Interference Filter.

1. INTRODUCTION

A filter which possesses a region of transmission bounded on either sides by a region of rejection is known as a band-pass filter. For the broadest band-pass filter, the most suitable construction is a combination of long wave-pass and short wave - pass filters. For narrower filters, other methods are used, involving a single assembly of thin films to produce the pass and rejection bands. The narrow band-pass filters must have very steep cut-on and cut-off transmittance characteristics as well as very low transmittance at wavelengths other than the transmission wavelength, to avoid crosstalk between the different channels.The simplest of these is the Fabry-Perot filter, which has a pass band shape which is triangular and it has been found that it is possible to improve this by coupling simple filters in series in much the same way as tuned circuits. These couples arrangements are known as (multi-cavity filters) or (multiple half-wave filters), where the present work is involved in this field [1]-[2]. These types of filters composed of a stack of microscopically thin layers of materials.The reflections created at each interface between the layers combine through wave interference to selectively reflect some wavelengths of light and transmit others [3].Interference of light waves occurs whenever two or more waves overlap at a given point under certain conditions, amongst these conditions are : (i) The interfering waves have identical wavelengths. (ii) The interfering waves are coherent (they must maintain a constant phase with respect to each other)[4]. In all-dielectric transmission-band filters, the transmittance rises at some distance on either side of the transmission band. The distance over which the transmittance is low is called the rejection region. The position of the transmission band is variously specified by the wavelength λ_{max} at which the maximum transmission occurs, the wavelength, λ_o, about which the filterpass-band is symmetrical,or the spectral centerof the band [5]. The most common structure for narrow band-pass filters (multi-cavity band-pass filters) is an all-dielectric filter consisting of a quarter-wave optical thick layers for the mirrors and half-wave optical thick, or multiple half-wave optical thick layers for the spacers. Single cavity band pass filters have a triangular shape with high transmission at the center wavelength of the spacer [6]. Dielectric materials are preferred on the metals, because the metals have the absorption property, which increase the temperature of the coating and leads to damage it or decrease the reflectance and transmittance of the coating. While the dielectric materials have very low absorption which do not affect the reflectance and transmittance of the coating [7].Ultra narrowband optical fiber filters have attracted considerable attentions for their various applications such as all-fiber band-pass/band-stop filtering, resonant sensors, special wavelength selecting, noise reduction, differential absorption LIDAR etc. Besides the various possibilities of realizing those optical components using discrete or integrated micro-optical elements, phase shifts in Bragg gratings are of particular interest due to the gratings' inherent low loss and absence of critical alignment requirements [8]. In this paper, we design ultra-narrow bandpass filter in the infrared region and study the performance of the filter under oblique incidence of the electromagnetic rays.

2. THEORETICAL BASIS

When plane electromagnetic wave is normal incident from air (refractive index n_o) to the surface (refractive index n_s), The reflectance R, given by[1]:

$$R = \left(\frac{n_o - n_s}{n_o + n_s}\right)\left(\frac{n_o - n_s}{n + n_s}\right)^{*} \text{.......(1)}$$

Analysis of a multilayer dielectric stack is similar to a boundary value problem. Thin film filters usually consist of a number of boundaries between various homogeneous media and it is the effect which these boundaries will have on the incident wave that we have to calculate [9]. For a general case of assembly of layers, the characteristic matrix is simply the product of the individual matrices taken in the correct order and is denoted by N [10]:

$$\begin{bmatrix} B \\ C \end{bmatrix} = \left\{ \prod_{r=1}^{N} \begin{bmatrix} \cos\delta_r & i\sin\delta_r/\eta_r \\ i\eta_r \sin\delta_r & \cos\delta_r \end{bmatrix} \right\} \begin{bmatrix} 1 \\ \eta_{sub} \end{bmatrix} \quad ....(2)$$

$$_r = y\cos\theta \quad \text{for s} - \text{polarization (TE Polarized light), and; ... (3)}$$

$$_r = \frac{y}{\cos\theta} \quad \text{for P} - \text{polarization(TM Polarized light)} \quad ......(4)$$

$$\delta_r = 2\pi n\, d_r\, (\cos\theta)/\lambda \quad .....(5)$$

N - number of layers, δ - phase term, η - optical admittance of the layers, t_p- physical thickness of the layer, λ–wavelength, θ_p - angle of incidence, B and C are the total electric and magnetic field amplitudes. The reflectivity of an assembly of thin films is calculated through the concept of the optical admittance. The multilayer can be replaced by a single surface, which has an input optical admittance Y given by:

$$Y = C / B \quad ....(6)$$

Y: is the admittance presented to the incident wave by the coating. The admittance presented by simple interface between two media is indistinguishable from the reflectance at that interface. This concept is used to calculate the reflectance of an assembly of thin films and the transmittance and be derived through the relationship of T=(1-R). The expressions for reflectance, transmittance are:

$$R = \left(\frac{\eta_o B - C}{\eta_o B + C}\right)\left(\frac{\eta_o B - C}{\eta_o B + C}\right)^*$$

Or;

$$R = \left(\frac{\eta_o - Y}{\eta_o + Y}\right)\left(\frac{\eta_o - Y}{\eta_o + Y}\right)^*$$

And

$$T = \frac{4\eta_o \mathrm{Re}(\eta_{sub})}{(\eta_o B + C)(\eta_o B + C)^*} \quad ....(7)$$

3. THE SUGGESTED FILTER DESIGNS

Constructive and destructive interference occurs between reflections from various layers will determine transmission depending on thickness of the dielectric layers, number of these layers, angle of incidence light on the filter. In the first step, we only varying the number of layer. The proposed designs are constructed of two dielectric materials, Zinc sulfide (ZnS) and Lead telluride (PbTe) as low (n_{ZnS}=2.3) and high (n_{PbTe}=5.5) refractive index respectively to coating germanium (Ge) as a substrate. with (N=1) of the spacer layerof material with high refractive index. In the second step, the same procedure of step one are repeated except the order of the spacer layer(N=2). The proposed designs are shown in table (1).Figure 1 and 2 shows transmittance versus wavelength of six suggestion designs. It is clear that the full width at half maximum (FWHM) decreases with increase the number of layer and the number of spacer, the results obtained from these figures are summarized in table (2).

Table 1: Suggestion designs of ultra-narrow band pass filter

Design number	Filter design	Order of spacer (N)
1	AIR /$(HL)^2$(HH) $(LH)^2$ L$(HL)^2$(HH) $(LH)^2$/SUB	N=1
2	AIR /$(HL)^3$(HH) $(LH)^3$ L$(HL)^3$(HH) $(LH)^3$ /SUB	N=1
3	AIR /$(HL)^4$ (HH) $(LH)^4$ L$(HL)^4$(HH) $(LH)^4$ /SUB	N=1
4	AIR/$(HL)^2(HH)^2(LH)^2$ L$(HL)^2(HH)^2(LH)^2$/SUB	N=2
5	AIR/$(HL)^3(HH)^2(LH)^3$ L$(HL)^3(HH)^2(LH)^3$ /SUB	N=2
6	AIR/$(HL)^4(HH)^2(LH)^4$ L$(HL)^4(HH)^2(LH)^4$ /SUB	N=2

Table 2: Transmittance and FWHM of Suggestion designs

Design number	Transmittance (%)	FWHM in nm	The resulting shape
1	98.07	60	Good
2	98.07	9	Very good
3	98.07	2	Excellent
4	98.07	35	Good
5	98.07	6	Very good
6	98.07	2	Excellent

A comparison between the designs will choose the best design, which is:

AIR/$(HL)^4$ $(HH)^2$ $(LH)^4$ L$(HL)^4$ $(HH)^2$ $(LH)^4$ /SUB

We will study, in the next section, the effect of the angle of incidence on the transmittance spectrum change for the filter proposed.

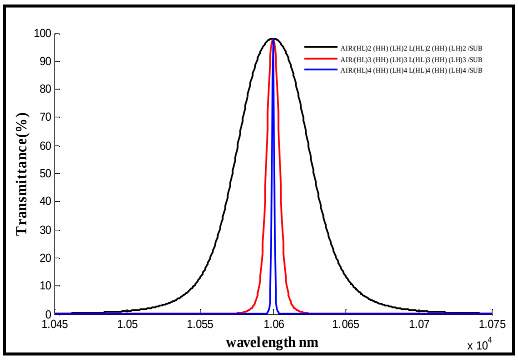

Figure 1: Transmittance as a function of wavelength at normal incidence for three designs:
(a)- AIR/$(HL)^2$ (HH) $(LH)^2$ L$(HL)^2$ (HH) $(LH)^2$ /SUB
(b)- AIR/$(HL)^3$ (HH) $(LH)^3$ L$(HL)^3$ (HH) $(LH)^3$ /SUB
(c)- AIR/$(HL)^4$ (HH) $(LH)^4$ L$(HL)^4$ (HH) $(LH)^4$ /SUB

4. EFFECT OF VARYINGANGLE OF INCIDENCE

At normal incidence, the filter transmitted S- Polarized or transverse-electric (TE- the electric filed perpendicular to the plane of incidence) and P- Polarized or transverse-magnetic (TM-the electric filed parallel to the plane of incidence) light equally. S and P polarization performance separate as the angle of incidence is increased away from normal [11]. The average performance is the average of S and P performance. Figure 3 shows the effect of varying angle of incidence in the range (0-60°) on the values of transmittance spectrum for both modes of polarization (S-polarization) and (P-Polarization).For collimated light and small angles of incidence, the shift in peak wavelength can be estimated using the following formula[12]:

$$\lambda_\theta = \lambda_\circ \left[1 - \frac{n_o}{n}\sin^2\theta\right]^2 \qquad \ldots\ldots\ldots\ldots(8)$$

Where: λ_θ , $\lambda_\circ$ peak wavelengths at incident angle (θ) and normal incident respectively, θ- angle of incidence, n_o- refractive index and n- effective refractive index of filter assembly. At small angles this shift can be very useful in tuning a filter to a desired peak wavelength but larger angles (30 degrees or more) can cause a fall in the average transmittance. The drop in the transmittance of TE-mode is larger than that of TM-mode, this result can be interpreted depending on the values of effective refractive indices which related to angle of incidence as shown in equations (3 & 4).

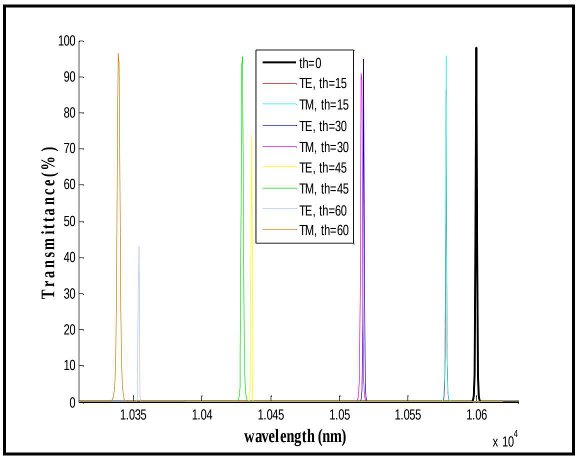

Figure 3: Transmittance of TE and TM modes as a function of wavelength at non-normal incidence(θ=15, 30, 45 and 60o) for the design:AIR/(HL)4 (HH)2 (LH)4 L(HL)4 (HH)2 (LH)4 /SUB

Figure 3 shows transmittance of TE and TM modes as a function of wavelength for oblique incidence ((θ=15, 30, 45 and 60o) for the proposed ultra-narrow bandpass filter design as comparing with normal incidence (dark line). As the angle of incidence increases, the optical phase thickness of a layer decreases (this clear from equation 5) , and both transmission bands of TE and TM polarized light shift to the shorter region. Also, as the angle of incidence increases, the admittance of TM polarization increases and that of TE polarization decreases, so the transmission bandwidth of TM polarization is wider than that at normal incidence, and that of TE polarization is narrower. There for, at a high incident angle and reference wavelength, the transmittance of TE- polarized light may be quite low in contrast to the high transmittance of TM- polarized light. The obtain results from figure 3 are summarized in table 3.

Table 3: Transmittance of TE and TM modes at non-normal incidence.

Incidence angle (degree)	TE-Mode	TM-Mode
0	98.07	98.07
15	94.58	95.81
30	95.01	90.77
45	73.78	95.37
60	42.93	96.34

5. CONCLUSION

Ultra-narrow bandpass filter in IR region has been theoretical designed at reference wavelength (λ_o=10600 nm) by using two optical material (ZnS and PbTe) as a low and high refractive index respectively to coated Ge as a substrate. The result of angle incidence effect on filter shows shift in reference wavelength with an increase in the incident angle with decreases in the transmittance for both type of S and P polarization, on the other hand the full width at half maximum (FWHM) of TM polarization is wider than that of TE polarization. The featureof shift in central wavelength (wavelength design) can be very useful in tuning a narrowband filter to the desired wavelength which may be used in some application that needed tilted filters

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