Design and Simulation of Optical Filter for Dense Wavelength Division Multiplexing (DWDM) System

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Received on 18/9/2012 & Accepted on 4/4/2013

ABSTRACT

In this paper, it is demonstrated, by means of simulations, the practical feasibility of an interference filter, implemented from a stack of high and low index birefringent thin films that can be used as transmission filter. Simulations were carried out with a software toolbox package implemented as Matlab™ m-files. The simulation is done by using the following linear material (AgB, ZnSe, KF2, GaAs, BaF2, TiO2) as coating material with single FBR (fabry perot resonator) structure , and KB7 glass as substrate material. Result show that difference between the values of refractive index of multi layer stack has great influence on the transmittance value, the largest possible value is the best choice for obtaining nearly 100% transmittance for the designed wavelength taken and this clearly observed in the simulation figures. In addition, Number of antireflection layer (N) effect clearly on the result, the design parameter that take GaAs as high refractive index material and BaF2 as low index material with N=4 represent good approach to the desired value for the simulated filter that's used in (DWDM) .

Keyword: Optical Filter, Fabry Perot Resonator, Anti Reflecting Coating.

تصميم ومحاكاة مرشح بصري لنظام المتعدد لاقسام الطول الموجي الكثيف

الخلاصة

يهدف هذا البحث الى محاكاة عمل المرشح البصري الناقل والمستخدم ضمن الاتصالات البصرية حيث تم الاستعانة بمبادئ الطلاء بالمواد الثنائية , وتمت المحاكاة بالاستعانة ببرنامج Matlab™.حيث إنّ المحاكاة تعمل باستعمال الموادّ الخطيّة التالية (AgB، ZnSe، KF,GaAs، BaF2, TiO 2) كطلاء مادّة مع مرنان فابري بيروت وحيد التركيب، ومادة KB 7 كمادّة ركيزة للمرشح البصري.

اظهرت النتائج ان الاختلاف بين قيم معاملات الانكسار للطلاء ذو الطبقات المتعددة له تأثير عظيم على قيمة النفاذية حيث ان القيمة المحتملة الأكبر تمثل أفضل اختيار للحصول على نفاذية تامة تقريبا لطول الموجة المصمّم . بالإضافة،الى ان عدد الطبقات المضادّة للإنعكاس (N) لها

https://doi.org/10.30684/etj.31.11A8
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تأثير بشكل واضح على النتيجة، وان التصميم الوارد بالبحث والذي اعتمد علي GaAs كمادّة ذات معامل انكسار عالية وBaF 2 كمادة ذات معامل انكسار واطئة مع N =4 تمثّل حالة من الحالات الشبه مثالية التي تحاكي القيمة المطلوبة للمرشح المقلّد الذي مستعمل في الاتصالات البصرية.

INTRODUCTION

The reflection bands of a dielectric mirror arise from the N-fold periodic replication of high/low index layers of the type $(HL)^N$, where H and L can have arbitrary lengths. Here, we will assume that they are quarter-wavelength layers at the design wavelength λ_0.A quarter-wave phase-shifted multilayer structure is obtained by doubling $(HL)^N$ to $(HL)^N(HL)^N$ and then inserting a quarter-wave layer L between the two groups, resulting in $(HL)^N L(HL)^N$. it can be refer to such a structure as a Fabry-Perot resonator (FPR) also it can be called a quarter-wave phase-shifted Bragg grating .

A FPR behaves like a single L-layer at the design wavelength λ0. Indeed, noting that at λ0 the combinations LL and HH are half-wave or absentee layers and can be deleted. Thus, the number of the HL layers can be successively reduced, eventually resulting in the equivalent layer L (at λ_0):

$$(HL)^N L(HL)^N \rightarrow (HL)^N-1L(HL)^{N-1} \rightarrow (HL)^{N-2}L(HL)^{N-2} \rightarrow \cdots \rightarrow L$$

Adding another L-layer on the right, the structure $(HL)^N L(HL)^N L$ will act as 2L.this structure operate as a half-wave absentee layer at λ0. If such a structure is sandwiched between the same substrate material, say glass, then it will act as an absentee layer, and it will open up a narrow transmission window at λ_0 in the middle of its reflecting band.

Without the quarter-wave layers L present, the structures $G|(HL)^N(HL)^N|G$ and $G|(HL)^N|G$ act as mirrors, but with the quarter-wave layers present, the structure $G|(HL)^N L(HL)^N L|G$ acts as a narrow transmission filter, with the transmission bandwidth becoming narrower as N increases.

By repeating the FPR $(HL)^{NL}$ $(HL)^N$ several times and using possibly different Lengths N, it is possible to design a very narrow transmission band centred at λ0 having a flat pass band and very sharp edges, such filter designs have been used in thin-film applications and in fiber Bragg gratings, for example, as demultiplexers for WDM systems and for generating very narrow-bandwidth laser sources (typically at λ_0 = 1550 nm) with distributed feedback Lasers [1-10].

In fiber-optic communications, wavelength-division multiplexing (WDM) is a technology which multiplexes a number of optical carrier signals onto a single optical fiber by using different wavelengths (i.e. colors) of laser light. This technique enables bidirectional communications over one strand of fiber, as well as multiplication of capacity.

The term wavelength-division multiplexing is commonly applied to an optical carrier (which is typically described by its wavelength).

A WDM system uses a multiplexer at the transmitter to join the signals together, and a demultiplexer at the receiver to split them apart. With the right type of fiber it is possible to have a device that does both simultaneously, and can function as an optical add-drop multiplexer. The optical filtering devices used have conventionally been etalons, stable solid-state single-frequency Fabry–Perot interferometers in the form of thin-film-coated optical glass.

WDM systems are popular with telecommunications companies because they allow them to expand the capacity of the network without laying more fiber. By using WDM and optical amplifiers, they can accommodate several generations of technology development in their optical infrastructure without having to overhaul the backbone network. Capacity of a given link can be expanded simply by upgrades to the multiplexers and demultiplexers at each end.

Early WDM systems were expensive and complicated to run. However, recent standardization and better understanding of the dynamics of WDM systems have made WDM less expensive to deploy.[16]

Optical receivers, in contrast to laser sources, tend to be wideband devices. Therefore the demultiplexer must provide the wavelength selectivity of the receiver in the WDM system.

WDM systems are divided into different wavelength patterns, conventional/coarse (CWDM) and dense (DWDM). Conventional WDM systems provide up to 8 channels in the 3rd transmission window (C-Band) of silica fibers around 1550 nm. Dense wavelength division multiplexing (DWDM) uses the same transmission window but with denser channel spacing. Channel plans vary, but a typical system would use 40 channels at 100 GHz spacing or 80 channels with 50 GHz spacing. Some technologies are capable of 12,5 GHz spacing (sometimes called ultra dense WDM). Such spacings are today only achieved by Free space technology.[17]

Analysis of the filter based on the fabry-perot interferometer

A conventional filter has a sandwich structure in which a dielectric (buffer) layer is placed between multilayer dielectric mirrors. First, note that the buffer layer of a conventional filter is a waveguide with leakage modes.

A dielectric mirror consists of multiple thin layers of (usually two) different transparent optical materials (dielectric coatings, thin-film coatings, interference coatings). Even if the Fresnel reflection coefficient from a single interface between two materials is small (due to a small difference in refractive indices), the reflections from many interfaces can (in a certain wavelength range) constructively interfere to result in a very high overall reflectivity of the device. The simplest and most common design is that of a Bragg mirror, where all optical layer thickness values are just one-quarter of the design wavelength. This design leads to the highest possible reflectivity for a given number of layer pairs and given materials. [11]

The number of thin-film layers required depends very much on the required function and on the refractive index difference between the coating materials.[12], the transfer matrix for one double layer of ($\lambda/4$) thick coating at normal incidence in the product of the individual film matrices , just as in the case of the double – layer anti reflecting films:

$$m_{HL} = m_L\, m_H \qquad \text{... (1)}$$

$$m_{HL} = \begin{bmatrix} 0 & i/\gamma_H \\ i/\gamma_H & 0 \end{bmatrix} \begin{bmatrix} 0 & i/\gamma_L \\ i\gamma_L & 0 \end{bmatrix} = \begin{bmatrix} -\gamma_L/\gamma_H & 0 \\ 0 & \gamma_H/\gamma_L \end{bmatrix} \qquad \text{... (2)}$$

$$m = (m_{H1}\, m_{L1})(m_{H2}\, m_{L2})\ldots(m_{HN}\, m_{LN}) = (m_H m_L)^N = (m_{HL})^N \qquad \text{...(3)}$$

Then the transfer matrix is

$$m = \begin{bmatrix} -\gamma_L/\gamma_H & 0 \\ 0 & -\gamma_H/\gamma_L \end{bmatrix}^N = \begin{bmatrix} (-\gamma_L/\gamma_H)^N & 0 \\ 0 & -\gamma_H/\gamma_L{}^N \end{bmatrix} \quad \text{... (4)}$$

For normal incidence

$$\frac{\gamma_L}{\gamma_H} = \frac{n_L}{n_H} \quad \text{and} \quad \frac{\gamma_H}{\gamma_L} = \frac{n_H}{n_L} \quad \text{... (5)}$$

So that

$$m = \begin{bmatrix} (-n_L/n_H)^N & 0 \\ 0 & (-n_H/n_L)^N \end{bmatrix} \quad \text{... (6)}$$

the matrix representing N high –low double layers of λ/4 thick coating in series are thus.

$$m_{11} = \left(\frac{-n_L}{n_H}\right)^N, \quad m_{22} = \left(\frac{-n_H}{n_L}\right)^N, \quad m_{12} = m_{21} = 0 \quad \text{...(7)}$$

Using these matrix elements in the expression for the reflection coefficient that is :

$$R = \frac{n_o(-n_L/n_H)^N - n_s(-n_H/n_L)^N}{n_o(-n_L/n_H)^N + n_s(-n_H/n_L)^N} \quad \text{... (8)}$$

When numerator of eq (8) are next multiplied by the factor $\left(\frac{-n_H/n_L)^N}{n_s}\right)$

And the result is squared to give reflectance:

$$R_{max} = \left[\frac{(-n_0/n_s)(n_L/n_H)^{2N} - 1}{(-n_0/n_s)(n_L/n_H)^{2N} + 1}\right]^2 \quad \text{... (9)}$$

The varying transmission function of a FBR is caused by interference between the multiple reflections of light between the two reflecting surfaces. Constructive interference occurs if the transmitted beams are in phase, and this corresponds to a high-transmission peak of the etalon. If the transmitted beams are out-of-phase, destructive interference occurs and this corresponds to a transmission minimum. Whether the multiply reflected beams are in phase or not depends on the wavelength (λ) of the light (in vacuum), the angle the light travels through the etalon (θ), the thickness of the etalon (ℓ) and the refractive index of the material between the reflecting surfaces (n).
The phase difference between each succeeding reflection is given by δ:

$$\delta = \frac{4\pi}{\lambda} n l \cos\theta \quad \text{... (10)}$$

If both surfaces have a reflectance R, the transmittance function of the etalon is given by

$$T_e = \frac{(1-R)^2}{1-R^2-2R\cos\delta} \quad ...(11)$$

$$T_e = \frac{1}{1+F\sin^2(\delta/2)} \quad ...(12)$$

Where F is called finesse,the transmission of an etalon as function of wavelength is shown below in Figure (1).

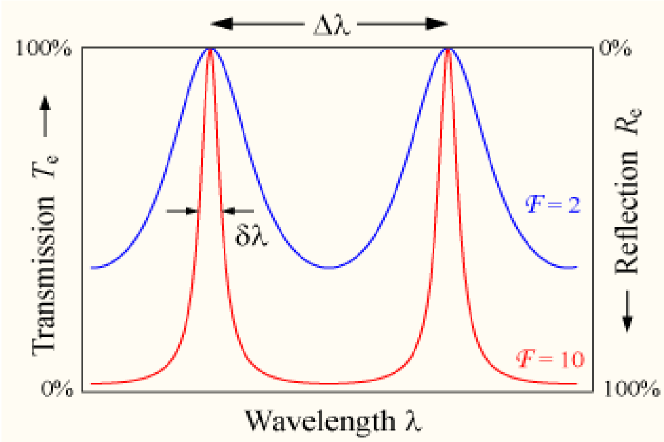


Figure (1) the transmission of an etalon as a function of wavelength, Etalon (F=10) shows sharper peaks and lower Transmission minima than etalon (F=2).

Maximum transmission (T_e=1) occurs when the optical path length difference (2nlcos δ) between each transmitted beam is an integer multiple of the wavelength. In the absence of absorption, the reflectance of the etalon R_e is the complement of the transmittance, such that (T_e+R_e)=1. The maximum reflectivity is given by:

$$R_{max} = \frac{4R}{(1+R)^2} \quad ...(12)$$

and this occurs when the path-length difference is equal to half an odd multiple of the wavelength.

The wavelength separation between adjacent transmission peaks is called the free spectral range (FSR) of the etalon, Δλ, and is given by:

$$\Delta\lambda = \frac{\lambda_0{}^2}{2nl\cos\theta+\lambda_0} \quad ...(13)$$

where λ_0 is the central wavelength of the nearest transmission peak. The FSR is related to the full-width half-maximum, δλ, of any one transmission band by a quantity known as the finesse:

$$F = \frac{\Delta\lambda}{\delta\lambda} = \frac{\pi}{2\operatorname{asin}(1-\sqrt{F}\,)} \quad ...(14)$$

Etalons with high finesse show sharper transmission peaks with lower minimum transmission coefficients.

SIMULATION AND RESULT PROPOSED ON FILTER

The following simulations concern to optical birefringence filters with design wavelength λ_0=1550 nm and the transmittance plotted over the range 1200 nm $\leq \lambda \leq$ 2000 nm.

The structure of the first filter can be represented as follows: $G(HL)^6L(HL)^6$ LG where the exponent numbers represents a layer repetition.

In Figure (2) Transmission filter design with One FPR. This figure illustrates the basic transmission properties of FPR filters. The parameters choose that might closely emulate the case of a fiber Bragg grating for WDM in present applications. The refractive indices of the left and right substrates and the layers are:

na = nb = 1.52, $n_L(BaF_2)$ = 1.4693, and n_H (ZnSe)= 2.5. The design wavelength at which the layers are quarter wavelength is taken to be the standard laser source λ0 = 1550 nm.

First, comparison between dielectric mirror of G $(HL)^6$ G and its phase-shifted version using a single FPR $G(HL)^6L(HL)^6$ LG , with number of layers N1 = 6.

It can be observe from Figure (2) that the mirror (case F_2) has a suppressed transmittance over the entire reflecting band, where as the FPR filter (case F_1) has a narrow peak at λ_0. The asymptotic edges of the reflecting band are calculated from Eq(13). In which ρ is elementary reflection coefficients, both λ_1 and λ2 equations are:

$$\lambda_1=\frac{\pi(n_H l_H+n_L l_L)}{acos(-\rho)}, \quad \lambda_2=\frac{\pi(n_H l_H+n_L l_L)}{acos(\rho)}, \quad \Delta\lambda=\lambda_2-\lambda_1 \quad ...(13)$$

For obtain λ1 = 1790 nm and λ2 = 1380 nm, the width of Δλ must be equal to 410 nm.

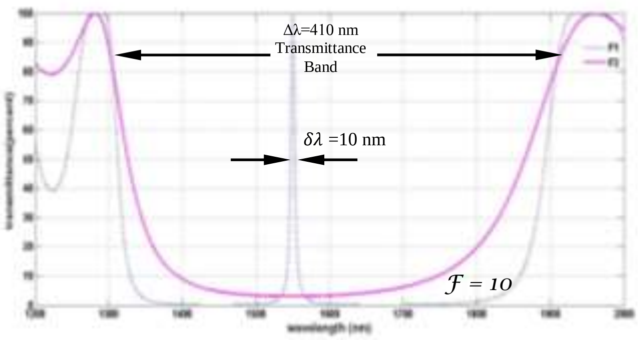


Figure (2) transmittance as function of wavelength for two cases (F_2 which represent Dielectric mirror of G|$(HL)^6$ |G structure, F_1 represent the structure $G(HL)^6L(HL)^6$ LG which is the Phase shift version of the dielectric mirror structure).

The location of the peak can be shifted by making the phase-shift different from λ/4. This can be accomplished by changing the optical thickness of the middle L-layer to some other value. The graph of Figure (3) show the case (F_3 where that length was chosen to be $n_L l_L = 0.6\ \lambda_0/4$ corresponding to shifts of 110nm i.e case F_3 represent the structure of $G(HL)^6\ 0.6L(HL)^6\ LG$ in which the same refractive index of Figure (2) has been taken with 6 layer.

It can be observe from Figure (3) that the mirror represent by case F_1 has a suppressed transmittance over the entire reflecting band, where as the FPR filter (case F_2) has a narrow peak at λ_0 with very small value for $\delta\lambda$ =15 nm which can be shifted by changing the thickness of sandwiched layer as shown clearly in case (F_3).

The asymptotic edge of the reflecting band of such cases are calculated and its values are $\lambda 1$ = 1400nm and $\lambda 2$ = 1730 nm , the width of $\Delta\lambda$ must be equal to 330 nm.

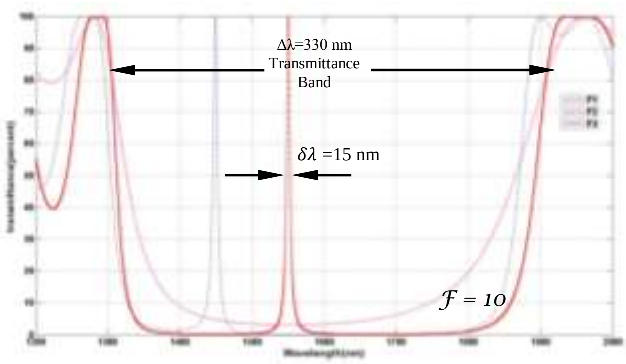


Figure (3) transmittance as function of wavelength for three cases (F_3 Represent shifting of 110 nm with structure $G(HL)^6\ 0.6L(HL)^6$ LG, F_2 which represent the structure $G(HL)^6L(HL)^6$ LG that is the phase shift version of the dielectric mirror structure, F_1which represent Dielectric mirror of $G|(HL)^6|G$ structure).

In Figure (4) it can be observed how filtering wavelength shifting again with different value than that of Figure (3) by choosing another value for the sandwiched layer (1.3L) and this clearly shown in case F_2,and by making comparison with the case (F_3) which represent the case of single FBR filter it can be conclude that a shift of 85nm can be achieved .

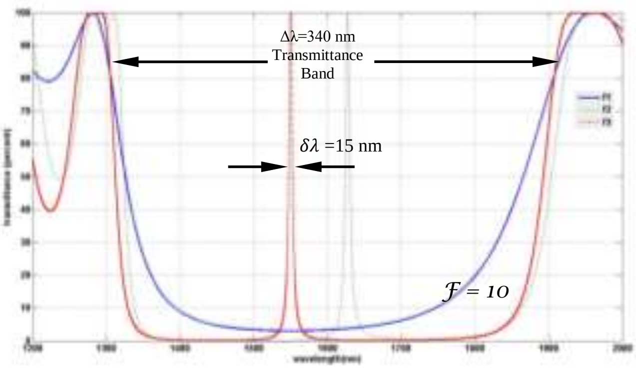
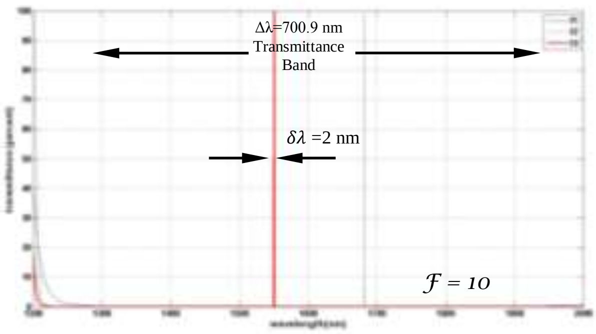


Figure (4) transmittance as function of wavelength for three cases (F_2 Represent shifting of 85nm with structure $G(HL)^6$ 1.3L$(HL)^6$ LG from F_2 which represent the structure $G(HL)^6L(HL)^6$ LG that is transmission filter with single FBR, F_1 represent Dielectric mirror of $G|(HL)^6|G$ structure , and again na = nb = 1.52, $n_L(BaF_2)$ = 1.4693, and n_H (ZnSe)= 2.5 with design wavelength =1550 nm).

The asymptotic edge of the reflecting band of the case of optical filter are calculated and its values are $\lambda 1$ = 1390nm and $\lambda 2$ = 1750 nm , the width of $\Delta\lambda$ must be equal to 340 nm and the value of $\delta\lambda$ is equal to 15 nm .

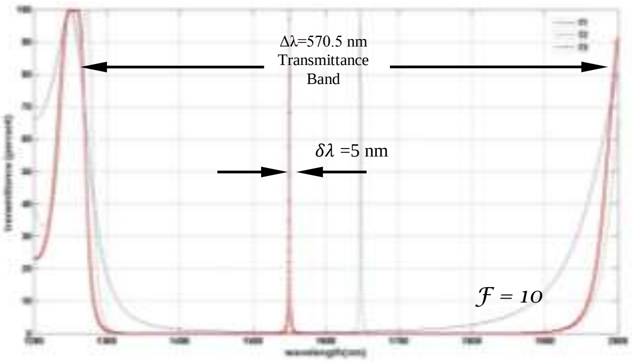
In Figure (5) the refractive indices of the layers were changed to study the effect of choosing another material for the anti reflecting coating layer ,which is n_H(GaAs)= 3.41917, and $n_L(BaF_2)$ = 1.449 , the design wavelength at which the layers are quarter wavelength is taken to be the standard laser source $\lambda 0$ = 1550 nm at which super narrow pulses are taken .It can be observed from Figure (5) that's the value for the edges of the transmittance band are changed from that of previous design which is $\lambda 1$ = 1270 nm and $\lambda 2$ = 1970.9 nm , resulting in a width of $\Delta\lambda$ = 700.9 nm. And also with different value of shifting that's equal to 128nm and the value of $\delta\lambda$ is equal to 2 nm .



Figure(5): transmittance as function of wavelength for three cases (F_2 Represent shifting of 128nm with structure $G(HL)^6$ 1.3L$(HL)^6$ LG , F_2 which represent transmission filter with single FBR that it has the structure $G(HL)^6L(HL)^6$, F_1which represent Dielectric mirror of $G|(HL)^6|G$ structure with 6 stack layer).

In figure (6) another design parameter are chosen in a try of reaching to beast result, first the refractive indices of the layers were changed to $n_H(TiO_2) = 2.48$, and $n_L(CaF_2) = 1.42692$, and other parameter are the same that of Figure (5).
It can be observed from Figure(6) that's the edged of reflection band are changed to λ1 = 1325 nm and λ2 = 1895.5 nm , resulting in a width of Δλ = 570.5 nm with shifting of 80 nm and the value of $\delta\lambda$ is equal to 5 nm .

unwanted transmittance wavelength between 1200nm up to 300nm,which makes the previous antireflection coating material is better than this.



Figure(6) transmittance as function of wavelength for three cases (F_3 Represent transmission filter with single FBR of structure $G(HL)^6 L(HL)^6$ LG , F_2 represent the of transmission filter with single FBR with 1.3 thickness of the sandwiched layer with structure of $G(HL)^6 1.3\ L(HL)^6$ LG , F_1represent Dielectric mirror of $G|(HL)^6|G$ structure).

In Figure (7) other group of refractive index for l material are chosen that is n_L (KF_2 = 1.88) , and n_H (ZnSe=1.71721) ,for the same design parameter of Figure 6.

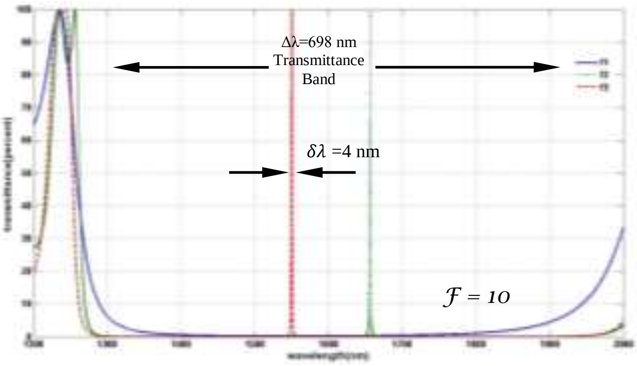


Figure (7) transmittance as function of wavelength for three cases F_3 Represent transmission filter with single FBR of structure $G(HL)^6 L(HL)^6$ LG , F_2 represent the of transmission filter with single FBR with 1.3 thickness of the sandwiched layer with structure of $G(HL)^6 1.3\ L(HL)^6$ LG , F_1represent Dielectric mirror of $G|(HL)^6|G$ structure).

It can be observed that from Figurer (7), the edged of transmittance band are λ1 = 1286 nm and λ2 = 1984 nm, resulting in a width of Δλ = 698 nm. With shifting of 111 nm. and the value of $\delta\lambda$ is equal to 4 nm . Unwanted transmittance wavelength between 1200nm up to 1390nm, which makes the previous antireflection coating material is better than this.

In Figure (8) it can be return to the case of Figure (2) to study the effect of changing number of layer N in our design, for the same other parameter .

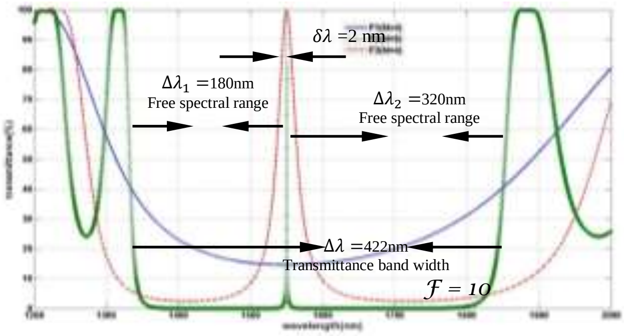


Figure (8) transmittance as function of wavelength for three cases (F2 Represent N=88 with structure G(HL)^6 L(HL)^6 LG , F3 represent N=4 which. represent the structure G(HL)^{4}L(HL)^4 LG that is the phase shift version of the dielectric mirror structure with N=4, F1represent Dielectric mirror of G|(HL)^4 |G structure with N_1=4).

It can be observed that from Figure (9) as N increased the value of Δλ will decreased and narrower peak at the design wavelength (1550nm).

For N= 8 the value of the edged of transmittance band are λ1 = 1368 nm and λ2 = 1790 nm , resulting in a width of Δλ = 422 nm. and the value of □□ is equal to 2 nm . and the value of free spectral range for the left hand side $\Delta\lambda_1$=180nm and for the right hand side $\Delta\lambda_1$=320nm .

In Figure (9) return to the case of taking GaAs as high index material and BaF_2 as low index material to study the effect of changing number of layer N for such case because it represent the perfect design parameter for our design.

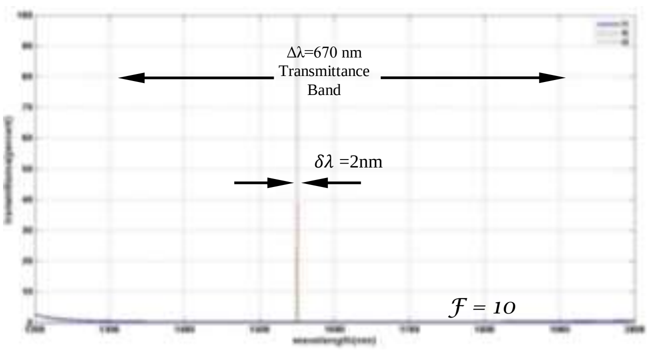


Figure (9) transmittance as function of wavelength for three cases (F_3 Represent N=6with structure G(HL)^6 L(HL)^6 LG , F_2 which represent the structure G(HL)^{4}L(HL)^4 LGthat is the mirror of G|(HL)N_1 |G structure where N_1=6).

It can be observed from Figure (9) that the parameter in which N =4 and n_H(GaAs) = 3.41917, and n_L(BaF_2) = 1.449 , the design wavelength at which the layers are quarter wavelength is 1550 nm at which super narrow pulses are taken and for single FBR transmission sandwiched thickness value can be taken according to the application required from them .

For N= 8 the value of the edged of transmittance band are λ1 = 1290 nm and λ2 = 1980 nm, resulting in a width of Δλ = 670 nm. And the value of $\delta\lambda$ is equal to 2 nm.

This structure represent the perfect design for our filter.

SIMULATION RESULT

Simulated filter show that's:

1. the location of the peak can be shifting according to the application required by choosing correct value of shifting differ from λ/4 by changing optical thickness of the middle L- layer to some other value.
2. Number of antireflection layer (N) affect clearly on the result , for our result research we aimed to reduced it as possible to achieved requirement .
3. the refractive index difference (Δn =nH-nL) has great influence on the transmittance value for single design wavelength , and the largest possible value is required , for which wide wavelength bandwidth (Δ λ) a achieved and clearly single wavelength taken with very suitable value of shifting for the same layer (L) thickness .
4. A WDM system uses a multiplexer at the transmitter to join the signals together, and a demultiplexer at the receiver to split them apart. With the right type of fiber it is possible to have a device that does both simultaneously, and can function as an optical add-drop multiplexer. The optical filtering devices used have conventionally been etalons, stable solid-state single-frequency Fabry–Perot interferometers in the form of thin-film-coated optical glass and this can be easily done by correct choice for the coating material which is represent the challenge factor for our design.

CONCLUSIONS

We conclude that the best value of parameter required for our design represent that taken in simulation Figure (9) with smallest value for N and largest value of Δn and largest value of shifting if required .

And such parameter are closely emulate of fiber Bragg grating of DWDM application. Optical receivers, in contrast to laser sources, tend to be wideband devices. Therefore the demultiplexer must provide the wavelength selectivity of the receiver in the WDM system and this can be done by the good choice for the transmission filter bandwidth that's depend on the design parameter which is control the value of transmittance band edge and the free spectral range and finally number of channel within transmission window.

Useful design rules for selecting refractive index in the sandwich layer have been provided. The transmission peak height is strongly dependent on the variation of sandwiched layer thickness.

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