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Design of Tunable Multiple- Cavity Filter for Optical Fiber Communication

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Abstract

In this paper a new type of cavity filter is investigated. The device is based on a Fabry–Perot interferometer which employing a cavity and two dielectric Bragg mirrors. The cavity filter uses multi layers of (SiO_2) and (ZnS) to produce a multi - layers ZnS/ SiO_2 cavity filter operating in the center wavelength of 1550 (nm). Zinc sulfide is used in this paper due to its high refractive index, while SiO_2 due to its low refractive index material. The filter is to be coated on Fused Silica having the index of 1.55 and operates at normal incidence. The ZnS/ SiO_2 thin film structure was designed using the Thin Film Design software (TF Calc). The simulation results show that the transmittance of the ZnS/ SiO_2 filter is about 95% for central wavelength of 1550 nm. This filter is essential for monitoring and reconfiguring optical networks.

Keywords: *Multiple cavity filter, optical communication, thin film layer.*

1. Introduction

Modern optical communication systems require ever increasing transmission capacity, which is nowadays provided by wavelength division multiplexing (WDM). Instead of installing new fiber links , additional individually modulated optical channels are added to already established transmission systems . These operate at fixed optical frequencies proposed by the International Telecommunication Union (ITU). The typical channel spacing is 200, 100 or even 50 GHz, which corresponds to wavelength steps of 1.6, 0.8 or 0.4 nm respectively.

With increasing channel number, high quality tunable devices become of great importance for flexible network management.

As a result, tunable filters represent key components in a large number of optical subsystems, such as wavelength – selective add –drop multiplexers, optical channel monitors and tunable lasers.

Non-tunable high performance multilayer designs are primarily used for fabrication of optical filters. Several concepts exist for realization of tunable interference filters, which make use of acousto-optic effects [1, 2] or are based on index tuning within liquid crystals [3]. Different approaches use fibers with optical multilayers deposited on the fiber end or gratings written into a fiber [4–6]. Micromechanically tunable devices feature distributed Bragg reflectors (DBR) in connection with a single air cavity of variable thickness.

Fabrication of these structures is mostly based on III–V semiconductors [7–11] whereby tuning is achieved by varying the distance between the mirrors.

2. Optical filter principle and structure

The present optical filter is based on a micro cavity, which consists of two coplanar reflectors separated by a solid state material. This structure resembles a classical Fabry–Perot cavity using distributed Bragg reflectors and is strongly reminiscent of a vertical cavity laser, as shown in figure 1.

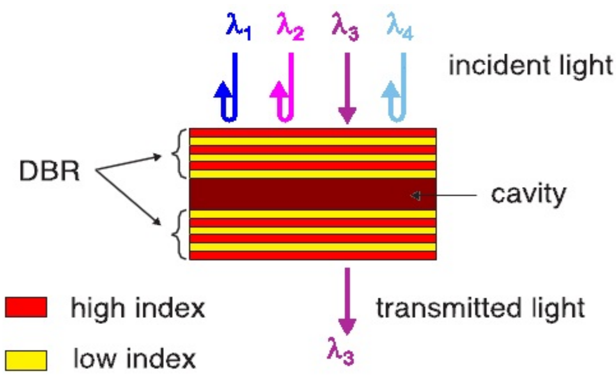

Fig 1. The filter structure consisting of a solid-state resonant cavity surrounded by two distributed Bragg reflectors (DBR). Each reflector consists of λ/4 thick layer pairs of high and low index materials. The structure is transparent for a wavelength defined by the resonance condition within the cavity, while the other part of the spectrum gets reflected

The thickness of the central cavity region is of the order of the wavelength of light. Plane waves propagating inside the cavity can interfere constructively and destructively such that only the resonant wavelengths are transmitted. As mentioned above, a pair of Bragg mirrors defines the resonator; each of these consists of N pairs of two materials with different refractive indices. Each layer has an optical thickness of λ/4, where λ is the Bragg wavelength for which maximum mirror reflectance occurs. Maximum reflectance increases with N and with the difference in refractive index. The shift in transmission wavelength is only determined by changes of the optical thickness of the cavity layer.[12-13]

3. OPTICAL INTERFACES

This section introduces the basis of the electromagnetic theory and its application in the calculation of the behavior of optical filters based in Fabry-Perot resonant cavities.

3.1 Principles of the propagation of the electromagnetic waves

The light is an electromagnetic wave, and the study of its propagation must start with the Maxwell equations. With the objective to become this study not very extensive, it will be started with some results of the Maxwell equations that are valid for linear media. A more detailed and rigorous approach
of the electromagnetic field equations can be found in [14].

3.2 Amplitude of the electromagnetic waves

An electromagnetic wave can be represented by:

$$\vec{E} = E_0 e^{j(wt-n.k.r)}$$
$$\vec{H} = H_0 e^{j(wt-n.k.r)} \qquad (1)$$

where $\vec{E}$ and $\vec{H}$ are respectively its electric and magnetic fields, ω is the optical angular frequency, K is the wave number (2 π / λ) and n is the refractive index of the propagation medium. If the propagation medium is absorbent, the refractive index must be substituted by n − jk , where k is the coefficient of extinction of the medium and j is the complex operator.
For a given wave, the relationship between the electric and magnetic fields is fixed and, in an isotropic medium, is given by:

$$\vec{H} = \sqrt{\frac{\varepsilon}{\mu}} n\vec{E} \qquad (2)$$

where ε and μ are the absolute dielectric and the induction
constants of the medium, respectively [15],

$$\varepsilon = \varepsilon_r \varepsilon_0$$
$$\mu = \mu_r \mu_0$$
$$\varepsilon_0 = 1/(\mu_0 c^2)$$
$$\mu_0 = 4\pi \times 10^{-7} NA^{-2}$$

where ε_r and μ_r are the relative dielectric and the induction constants of the medium, ε_0 and μ_0 are the dielectric and the induction constants of the free space and c is the speed of the light in vacuum. In an anisotropic media the equation (2)becomes more complex, since ε and μ are vectors instead of scalar quantities [16, 17].

The directions of the vectors $\vec{E}$ and $\vec{H}$ are also related, forming an angle of $\pi/2$ rad between them and with the direction of propagation. The direction of the propagation is given by the rule of the right hand.

3.3 Polarization

The light that travels in a given direction can have two independent polarizations. The light incident in a surface, forming an angle θ with its normal, can have either the electric field vector or the magnetic field vector parallel to the plane of incidence. In the first case, the polarization is p and in the second, the polarization is s. In a general way, the electric field vector forms an angle ϕ with the plane of incidence. In this in case, it can be decomposed in two components, one of polarization p and other of polarization s, being:

$$E_P = E\cos\phi\cos\phi \qquad \text{for P polarization}$$
$$E_s = E\sin\phi \qquad \text{for S polarization}$$

In a similar way, for the magnetic field vector:

$$H_P = H\cos\phi$$
$$H_S = -H\sin\phi\cos\theta$$

The normal refractive index n is equal to H/E. In a similar way , a generalized refractive index u can be defined for each of the polarizations, such that:

$$u_p = H_P / E_P = n / \cos\theta$$
$$u_s = H_s / E_s = H\cos\theta / E = -n\cos\theta$$

Notice that all the polarization states can be decomposed in the p and s components, possibly with a phase shift between them. This turns the following analysis useful for all the polarization states. In a general way, any optic interface has different properties for the two polarizations, except when the incident light is normal to the surface. In this case, the polarizations p and s are equivalent.

3.4 Boundary conditions

The boundary conditions in each interface between two different optical media derive from the electromagnetic theory
and allow establishing the relationship between the electromagnetic fields on one side of the interface with the ones on the other side. These conditions state that the components of E and H parallel to the interface must have the same value in both sides.

3.5 Properties of a thin film stack

In Figure. 2 a set of thin films with q interfaces, i. e., q −1 films is shown.

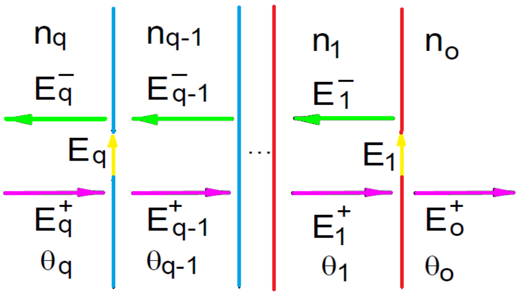

Figure 2. Thin film stack.

The film i has a wave traveling to the right, E_i^+ , and another one traveling to the left, E_i^- . They make an angle θ_i to the normal of the interface. The film has a refractive index n_i and a thickness d_i (not represented in the figure). Film 0 (at the right side) is the exit medium and the film q (at the left side) is the incidence medium. Usually, the incidence as well as the exit media of a film stack is constituted by air.
Assuming that the stack of thin films forms an optical filter, the beam of incident light is E_q^+, the reflected one is E_q^- and the transmitted one is E_0^+. E_0^- is equal to zero, once it is considered the case in which there is only one light source on the left side of the filter. In the case that several light sources exist , each one can be analyzed separately, once it is estimated that the optical medium is linear [18]. From here, only the values of the electric fields E_q^+, E_q^- and E_0^+ are important. All the other fields have interest only for the attainment of the three last ones.

3.6 Optical path

The phase thickness of the film i in the case of the light with normal incidence is given by:

$$g_i = \frac{2\pi u_i d_i}{\lambda}$$

where d_i is the thickness of the film and λ the wavelength of the light in the free space. The phase thickness represents the variation in phase that the light suffers when crosses the film [19]. In the most general case, where the light arrives with an angle θ_i , the expression of the phase thickness is:

$$g_i = \frac{2\pi u_i d_i \cos\theta_i}{\lambda}$$

where the angles θ_i are determined from the Snell law:

$$u_q \sin\theta_q = u_i \sin\theta_i = u_0 \sin\theta_0$$

The variable u_i will be u_{pi} in the polarization p and u_{si} in the polarization s. Notice that, in the case of the film i absorbing light, u_i is a complex quantity, what makes i a complex number too.

3.7 Equations in the interface between two films

First, it is assumed that the phase of the waves is zero in the interface between the films i and i −1 . In other words, the phase is zero at the right side of the film i. In the interface between the film i + 1 and i, at the left side of the interface the fields E_{i+1}^+ and E_{i+1}^- are present, and at the right side are present the fields $E_i^+ e^{jgi}$ and $E_i^- e^{jgi}$, where e^{jgi} and e^{-jgi} represent the phase shifts suffered by the electromagnetic waves along the film i.
Using the boundary conditions described previously, it comes to the interface

$$E_{i+1}^+ + E_{i+1}^- = E_i^+ e^{jgi} + E_i^- e^{-jgi} \quad (3)$$

It is convenient to define now:

$$E_i = E_{i+1}^+ + E_{i+1}^- \text{ and } H_i = H_i^+ + H_i^-$$

where E_i and H_i are the total fields in the interface between the films i and i − 1 . Knowing that $H_i^\pm = \pm u_i E_i^\pm$, then:

$$E_i^+ = \frac{1}{2}(E_i + H_i / u_i)$$
$$E_i^- = \frac{1}{2}(E_i - H_i / u_i) \quad (4)$$

Then the equation (3) becomes

$$E_{i+1} = \cos g_i E_i + \frac{j}{u_i} \sin g_i H_i \quad (5)$$

In a similar way, the following value for the magnetic field in the interface i + 1 , i is obtained:

$$H_{i+1} = j u_i \sin g_i E_i + \cos g_i H_i \quad (6)$$

The equations (5) and (6) can be written in a matrix form

$$\begin{bmatrix} E_{i+1} \\ H_{i+1} \end{bmatrix} = \begin{bmatrix} \cos g_i & j \sin g_i / u_i \\ j u_i \sin g_i & \cos g_i \end{bmatrix} \begin{bmatrix} E_i \\ H_i \end{bmatrix}$$

Or

$$\begin{bmatrix} E_{i+1} \\ H_{i+1} \end{bmatrix} = M_i \begin{bmatrix} E_i \\ H_i \end{bmatrix}$$

where the matrix M_i is given by

$$M_i = \begin{bmatrix} \cos g_i & j \sin g_i / u_i \\ j u_i \sin g_i & \cos g_i \end{bmatrix} \quad (7)$$

The matrix M_i of 2×2 elements contains all the details of the
film i and relates the values of E and H of one side of the film with the ones of the other side. It can also be written: In a general way the values of the electric and magnetic field in the exit medium, can be related with the ones in the incidence medium through the equation:

$$\begin{bmatrix} E_q \\ H_q \end{bmatrix} = M_{q-1} M_{q-2} \ldots M_2 M_1 \begin{bmatrix} E_0 \\ H_0 \end{bmatrix} \quad (8)$$

In this case, it was considered that $g_0 = 0$, reducing M_0 to the identity matrix.

3.8 Transmission and absorption coefficients

Now, it is necessary to calculate the values of the electric and magnetic fields of the incident, reflected and transmitted waves. To do that, it is necessary to go back to the equation (4)that, written in the matrix form, becomes:

$$\begin{bmatrix} E_q^+ \\ E_q^- \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & 1/u_q \\ 1 & -1/u_q \end{bmatrix} \begin{bmatrix} E_q \\ H_q \end{bmatrix} \quad (9)$$

And

$$\begin{bmatrix} E_0 \\ H_0 \end{bmatrix} = \begin{bmatrix} 1 \\ u_0 \end{bmatrix} E_0^+ \quad (10)$$

as $E_0^- = 0$

Combining the equations (8), (9) and (10), comes

$$\begin{bmatrix} E_q^+ \\ E_q^- \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & 1/u_q \\ 1 & -1/u_q \end{bmatrix} M_{q-1} \ldots M_1 \begin{bmatrix} 1 \\ u_0 \end{bmatrix} E_0^+ \quad (11)$$

From equation (11), the transmission and reflection coefficients are:

$$r = E_q^- / E_q^+ \qquad t = E_0^+ / E_q^+$$

and for the reflectivity and transmissivity comes respectively

$$R = |r|^2 = |E_q^- / E_q^+|^2 \qquad T = \frac{u_0}{u_q} t = \frac{u_0}{u_q} |E_0^+ / E_q^+|^2 \quad (12)$$

3.9 Fabry-Perot optical filter

The Fabry-Perot optical filter is an optical interface constituted by two films of high refractive index placed at both sides of a film of low refractive index, as it is shown in Figure. 3.

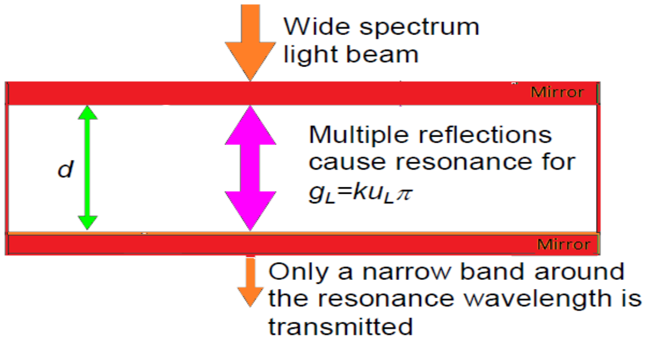

Fig. 3. Fabry-Perot optical filter.

In this case, the incidence and the exit media are constituted by air, whose refractive index is approximately equal to 1. As $u_q = u_0 = 1$, Equation (11) becomes:

$$\begin{bmatrix} E_q^+ \\ E_q^- \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} M_H M_L M_H E_0^+ \quad (13)$$

where M_H and M_L represent the film matrixes of the high and low refractive index films respectively, and are given by equation (7). The transmissivity of the filter is then calculated using equation (12).
By analyzing equations (7) and (13), it is possible to conclude that the transmissivity of the Fabry-Perot optical filter depends, among other parameters, on the thickness of the lowrefractive index film. Actually, the resonant condition is achieved when the phase change in the low refractive index film is null, i. e. cos = 1 gL . This condition is achieved making g_l = k π uL , k=0, 1, 2, … Therefore, in a Fabry-Perot optical filter the thickness of the resonance cavity determines the tuned wavelength.

4. The choice of materials

The development of optical filters for different wavelengths in is important for many communication

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instruments. Currently available filters are based on interference in multilayer stacks (so-called multilayer interference filters).

The material layer is required mainly for multilayer system have high transmittance in [20]. Taking into account that thin films in multilayer interference coatings must be dense and have low absorption in the wavelength range defined for the intended application [21].

The arrangement of material on two faces of substrate must be according to the value of refractive index. First material have higher refractive index than second material as consequently the light will be suffer many of refraction as Snell's law to obtain the desired wavelength as shown in figure 4

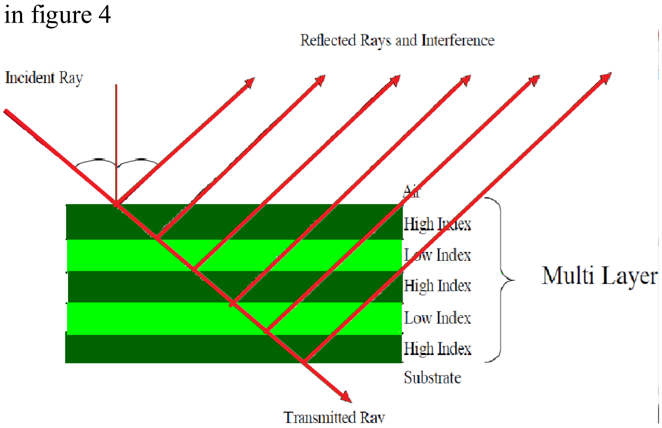

Fig4:. Reflection, Transmission and layers arrangement

When the difference in optical path length between the rays transmitted at successive reflections is such that the emerging waves are in the same phase, constructive interference will occur and filter will show the maximum transmittance value.

If this condition does not hold, the interference between successive emerging rays will be destructive and the transmission will be relatively low [22].

This filter design consist of two material. ZnS is high index layer and SiO_2 is low index layer . The wavelength range from 1000nm to 1800nm . The filter is to be coated on Fused Silica having index 1.55 and operates at normal incidence .

5. Results and discussion

In the present work, these theoretical designs have been suggested and their profiles have been fully studied for the visible region and near IR region using open filter software [23]. The technology of DWDM is one of the most recent and important technique in the development of fiber optic communication technology.

The band-pass filter used for detecting light at range wavelength 1000nm-1800nm as in design below out of these wavelengths the filter is allowed to transmit nearly zero as in figure 5. The filter is to be coated on Fused Silica having index 1.55. The filter operates at normal incidence. The most common structure for narrow band-pass filters (multi-cavity band-pass filters) is an optical thin film 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. So that the open filter program can be used to design this filter, we use ZnS and SiO_2 as the two coating materials. The layers structures of narrow band pass filter for two designs can be see below. The characteristics transmission vs wavelength clearly seen from figure 5 which shows the center to center spacing of the channels in wavelength units.

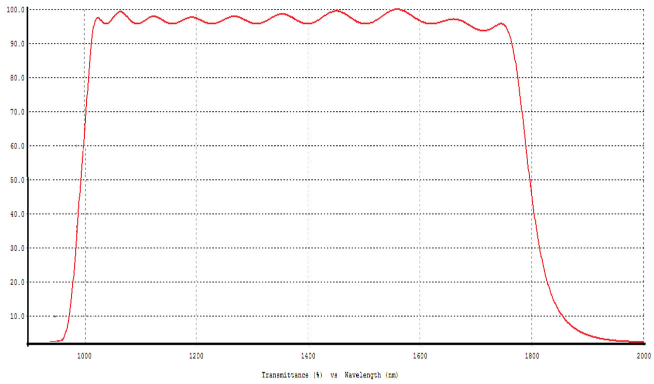

Fig 5.Transmition vs wavelength for Proposed optical Filter

6. Conclusion

In this paper , the design of an optical filter at a wavelength of 1550 nm is considered . This filter is useful for telecommunications industry to control the transmission through fiber optic cables. to do this , at first the structures of optical filter is studies . factors influencing transmission spectrum of filter is investigated. These factors are thickness of layer and index material of layer.

Proposed filter was simulated by using TFCalc that indicate transfer coefficient above 95% in desired spectrum .in comparing with Ge/MgF2 filter advantage of designed filter than previous filters is determined .having more transfer coefficient and having flat and rectangular shape in it's transmission spectrum are among it's advantage .This filter cheaper than Ge/MgF2 filter because ZnS layer is cheaper than Ge layer .number of layer`s filter and general thickness of filter is lower than Ge/MgF2 filter. also adjustable power of proposed filter is one of important advantage . when the number and thickness of different layer has changed , filter can be adjusted properties to the desired bandwidth.

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