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Design of Optical Thin Film Filter for Sensor Network

Vahideh Khadem Hosseini*, Mohammad Taghi Ahmadi***

Abstract

Human body detection is very important especially in the countries prone to earthquakes. Fabry-Perot filter as an ideal option in this field needs to be explored. This filter is useful for detection of objects that have temperature around that of the human body. In the presented research, an optical thin film Fabry-Perot filter (FPF) at the wavelength about 8 um to 14 um is investigated .The important factors on transmission spectrum and the band width of filter are discussed. Additionally structural factors such as layers material and their thickness are explored. Various materials with high and low refractive index are examined by TFCalc3.5 for thin film layers. Germanium (*Ge*) with the refractive index 4.20 is selected for layer with high refractive index and Silicon Dioxide (SiO_2) with the refractive index 1.46 is selected for low refractive index layer. Our simulation results lead to optimum parameters as: Germanium layer with 196nm thickness and Silicon Dioxide layer with 451nm thickness. Simulation of proposed filter indicated that the transfer coefficient is more than 90% in desired spectrum. Filter structure can be used on Infrared detectors to improve their resolutions and detection.

Keywords: Infrared Detector, Fabry-Perot Filter, Sensor Network, Thin Film Layer

Introduction

Every year natural disasters cause death of thousands of humans all over the world. After an earthquake people get buried under quake rubble and determining their exact position becomes very important. In such conditions an instrument is needed that can detect humans based on body radiation frequency range without coming in direct contact (Haruyuki, 1999).Surface temperature of human body is of infrared (IR) wavelength and thermal sensor is an ideal option in this bandwidth (Komatsu, Mori, Sone & Kimura, 1996).

There are different ranges of frequency in environment around us and deleting unwanted bandwidth is very essential in infrared detectors. Fabry-Perot filter (FPF) is the best choice in such conditions (Neumann, Ebermann, Hiller & Kurth, 2007). The structure of detector with this filter is shown in Fig. 1. Important factors are thickness of thin film and layers material for setting optical filter in the desired range (Liu, Lee, Liao, Kaneko, Nakahira & Akano, 2008; Daleiden, Rangelov, Irmer, Römer, Strassner & Prott, 2002). In general, thin film materials are made of III–V semiconductors (Hohlfeld & Zappe, 2004).The structure of optical thin film filter is shown in Fig. 2.

Fig. 1: Detector with Fabry-Perotfilter (Neumann, Ebermann, Hiller & Kurth, 2007)

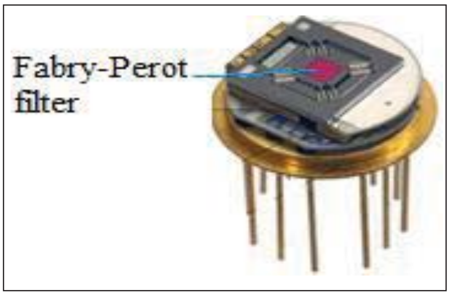

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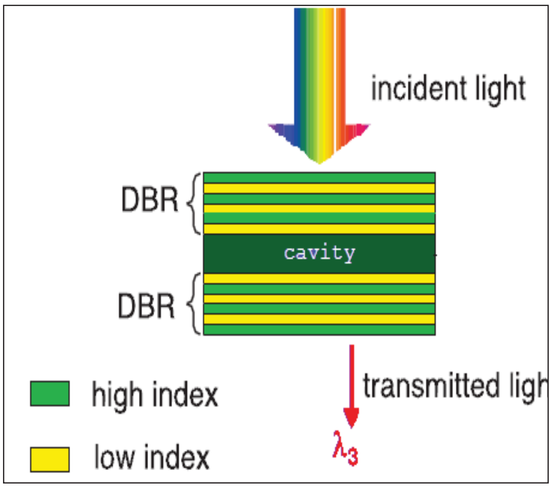
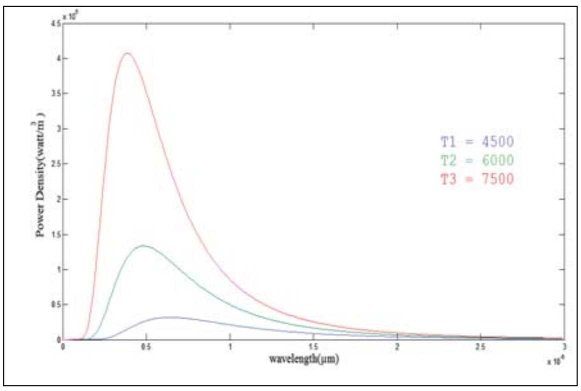
Fig. 2: Structure of Optical Thin Film Filter



Thermal Infrared Region

Today, environmental monitoring is an important subject in technology. It works based on difference in temperature betweene nvironment and objects. It expresses that anobject radiates specific wavelength. Stefan-Biltzmann's Law calculates value of object radiation (Zhao, Mao, Horowitz, Majumdar, Varesi & Norton, 2002; Spitzer, Ackerman, Scherzinger & Whitlock, 1996). Planck's Lawcan plan black-body radiation curve for an object. Black-body radiation curve of some temperature are shown in Fig. 3 (Planck, 1901). For a typical human body, this curve is in the thermal infrared region and its peak radiation occurs at 9.55 µm, therefore thermal sensor can detect it in "thermal imaging" region (Buser & Tompsett, 1997; Kakuta, Yokoyama & Nakamura, 2001; http://en.wikipedia.org; http://www.glolab.com).

Fig. 3: Black-Body Radiation Curve in Different Temperature



Thin Film Interference Filter

An optical filter consists of several thin films with different refractive indexes. Special bandwidth filter can be adjusted by changing material of layers and their thickness.

Analysis of a Multilayer with Dielectric Layers

There are several boundaries surrounded by two homogeneous media in optical filters and they effect on incident wave. Reflection and transmission coefficients of single boundary with "s" and"p" polarisation are calculated by Fresnel equations.

$$r_s = \frac{n_i \cos\theta_i - n_t \cos\theta_t}{n_i \cos\theta_i + n_t \cos\theta_t}$$

$$t_s = \frac{2n_i \cos\theta_i}{n_i \cos\theta_i + n_t \cos\theta_t}$$

$$r_p = \frac{n_t \cos\theta_t - n_i \cos\theta_t}{n_i \cos\theta_t + n_t \cos\theta_t}$$

$$t_p = \frac{2n_i \cos\theta_t}{n_i \cos\theta_t + n_t \cos\theta_t}$$

where n_i and n_t are boundary refractive indices. θ_i is angle of incident media and θ_t is transmitted media. If incidence is normal,angles will be $\theta_i = \theta_t = 0$ and the equation will change. If incidence is normal, angle of incident media, θ_i equals to angle of transmitted media.

$$r_s = -r_p = \frac{n_i - n_t}{n_i + n_t}$$

$$t_s = t_p = \frac{2n_i}{n_i + n_t}$$

Dielectric films need to two media with any absorbing and media simple boundaries between extended media and reflectance value of simple boundaries are different. So it is calculated with the help of explained equations then the best media is chosen.

Reflection of Thin Film

Equations of last part are calculated as reflection of thin film. Films have different characteristics. There is a way to determine them. At first the light indicates to multiple interfaces. Then sequential reflections in some interfaces cause multiple beams. These beams sum up which determines characteristics of the film.The film thickness affects coherence length of light and path difference between the different beams. Effects of thin film filter interference can be observed in the beams.

Passing polarized light through a thin film causes to increase multiple reflections at the interfaces. A sa result, two main beams of light reflect in opposite directions. Interference beams cause to fields at all points in the medium. These are electric field “E” and a magnetic field “H”. Field vectors are parallel to the interfaces in incident normally. In this condition, there is relation between fields at points. Field vectors “E′” and “H′”are related to field vectors “E” and “H”.

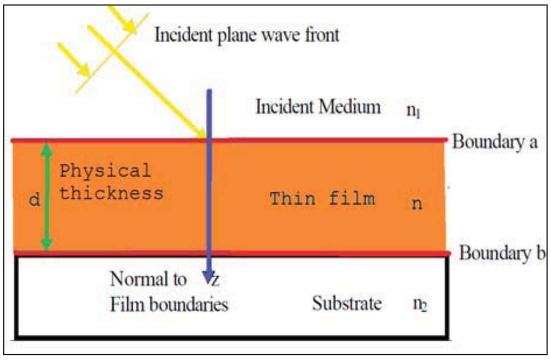
$$\begin{matrix} E \\ H \end{matrix} = \begin{matrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{matrix} \begin{matrix} E' \\ H' \end{matrix}$$

There are thin films between two points in a multilayer filter. Those are without contact to the environment around them. They can be an alysed using the Herpin matrices for continuous fields (Epstein, 1952). The determinant of Herpin matrices plane wave incidents on a thin film which is shown in Fig. 4. There are two boundaries “a, b” on two sides of thin film. Its matrix is given as

$$\begin{matrix} \cos\delta & \frac{(i\sin\delta)}{n} \\ in\sin\delta & \cos\delta \end{matrix}$$

In above matrix, “n” is the refractive index of the homogeneous film,“d” is the physical thickness of the film, and $\delta = 2p * n * d / \lambda$

Fig. 4: Plane Wave Incident on A Thin Film



$\delta = 2p * n * d / \lambda$

For light incident at an angle *θ*, matrices are determined by

$$\begin{matrix} E_a \\ H_a \end{matrix} = \begin{matrix} \cos\delta & \frac{i\sin\delta}{n} \\ in\sin\delta & \cos\delta \end{matrix} \cdot \begin{matrix} E_b \\ H_b \end{matrix}$$

Electric field and magnetic field at boundary “a”are “E_a”, “H_a”,respectively and fields at boundary “b”are “E_a”,,“H_a”, respectively. The optical admittance of the thin film is $Y = H_a/E_a$. Therefore

$$Y = \frac{n_2\cos\delta + in\sin\delta}{\cos\delta + i\frac{n_2}{n}\sin\delta}$$

Multilayer thin films consist of two or more thin films. The individual matrices of the two films affect its matrix.

The Herpin Index

Arrangement of thin films is symmetrical in some multilayer thin films. The mathematical equivalence of them is discussed in paper of Epstein in 1952. Usually, arrangement of three layers is “pqp”. The characteristic matrix of this structure is shown as

$$\begin{matrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{matrix} = \begin{matrix} \cos\delta_p & \frac{(i\sin\delta_{p)}}{n_p} \\ in\sin\delta_p & \cos\delta_p \end{matrix} \begin{matrix} \cos\delta_q & \frac{i\sin\delta_q}{n_q} \\ in_q\sin\delta_q & \cos\delta_q \end{matrix} \begin{matrix} \cos\delta_p & \frac{i\sin\delta_p}{n_p} \\ in_p\sin\delta_p & \cos\delta_p \end{matrix}$$

Therefore,

$$M_{11} = \cos 2\delta_p * \cos\delta_q - \frac{1}{2}\left(\frac{n_q}{n_p} + \frac{n_p}{n_q}\right)\sin(2\delta_p) * \sin\delta_q,$$

$$M_{12} = \frac{i}{n_p} \begin{matrix} \sin 2\delta_p * \cos\delta_q + \frac{1}{2}\left(\frac{n_q}{n_p} + \frac{n_p}{n_q}\right)\cos(2\delta_p) \\ * \sin\delta_q + \frac{1}{2}\left(\frac{n_p}{n_q} - \frac{n_q}{n_p}\right)\sin\delta_q \end{matrix},$$

$$M_{21} = in_p \begin{matrix} \sin 2\delta_p * \cos\delta_q + \frac{1}{2}\left(\frac{n_q}{n_p} + \frac{n_p}{n_q}\right)\cos(2\delta_p) \\ * \sin\delta_q - \frac{1}{2}\left(\frac{n_p}{n_q} - \frac{n_q}{n_p}\right)\sin\delta_q \end{matrix},$$

and $M_{11} = M_{22}$

Let M_{11} = cos γ = M_2 and $M_{12} = i\sin\gamma / E$. Its determinant is calculated and the resulting matrix is one, $M_{11}M_{22} - M_{12}M_{21} = 1$ so $M_{21} = iE\sin\gamma$.

Therefore,

$$\begin{matrix} \cos\gamma & \dfrac{i\sin\gamma}{E} \\ iE\sin\gamma & \cos\gamma \end{matrix}$$

If three films are symmetrical, there will be one dense film. So its matrix is same as matrix of single film. Refractive index and phase thickness are "E" and"γ" respectively. Therefore $E = \sqrt{\dfrac{M_{21}}{M_{12}}}$ is effective index and $\gamma = ar\cos(M_{11})$ is effective phase thickness. These equations can be used to any number of layers for symmetrical period.

Herpin index is a key mathematical tool in the design of thin film coatings. Wave number, polarisation and angle of incidence light affect its elements. Incidence angle is different. Its effect can not be calculated this way. Herpin index is a mathematical model and it isn't physical model exactly. In some physical aspects, the number of symmetrical layers can be reduced and they are equivalent single layer. Assume multilayer equivalent index and phase thickness to be "E" and "γ" respectively.If it is arranged N times, equivalent phase thickness will change to "N γ" and equivalent index will be "E". Therefore,

$$\begin{matrix} \cos\gamma & \dfrac{i\sin\gamma}{E} \\ iE\sin\gamma & \cos\gamma \end{matrix}^{N} = \begin{matrix} \cos(N\gamma) & \dfrac{i\sin(N\gamma)}{E} \\ iE\sin(N\gamma) & \cos(n\gamma) \end{matrix}$$

Signs of M_{12} and M_{21} are similar. Value of effective index "E" is real or complement imaginary. If it is image value, $|\cos\gamma|$ will be greater than one. Structure of thin film products is called stop-bands. It is noticeable in physical aspects. As the number of basic periods increase in a multilayer and $|M_{11}| = |M_{22}| \succ 1$ so the reflectance tends to acquire unity in regions. In special condition, multilayer reflectance is 100%. Also the stop-band is assumed with an imaginary index, phase thickness in the spectrum and $M_{11} = -1$ for edges of this stop-band.

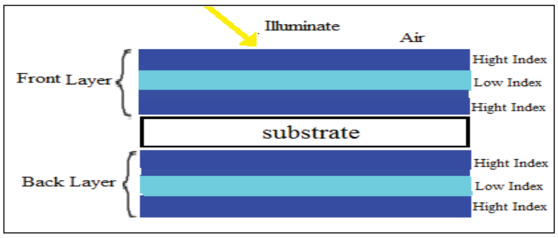
The detailed structure of Fabry-Perot filter can be divided in two types, one in which the membrane structures are (HL)H-2L-H(LH) and another in which it is (HL)-2H-(LH). "H" represents high-index dielectric medium with optical thickness of quarter-wave and "L" represents low-index dielectric medium with optical thickness of quarter-wave. The "H" layer and "L" layer are alternate anywhere except the spacer layer in which the medium consists of either two "H" layers or two "L" layers (Herpin, 1947).

The Choice of Materials

Infrared (IR) vision is a key technology in many astronomical and atmospheric instruments. Infrared multilayer filters consist of a number of layers. Every layer is made of special material. Materials must have high transmittance in the infrared region and high reflection in the visible region (Liu, Cai, Qiao, Mao & Jiang, 2003). For this property, absorption and interference of layers need to decrease (P`erez, Bernal-Oliva, M´arquez, Gonza´lez-Leal, Morant & Ge´nova, 2005). There are few materials sufficiently transparent beyond 15μm. It's a problem of multilayer interference filters in the far IR spectral ranges (Christophersen, Kochergin & Swinehart, 2004).

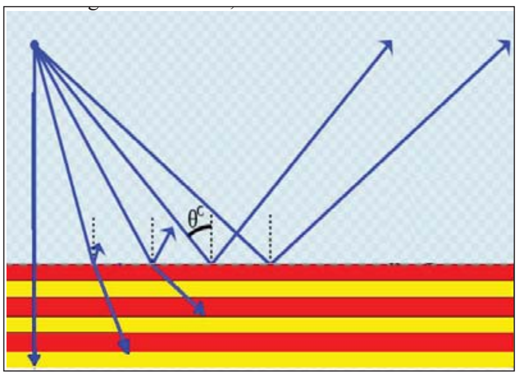
The value of refractive index is important for arrangement of material on two faces of substrate. Higher refractive index is put on substrate then lower refractive index is put on it. This arrangement of material is shown in Fig. 5.

Fig. 5: Arrangement of Material on two Faces of Substrate in Multilayer Filter



According to Snell's law, some refractions cause to achieve the desired wavelength. It is shown in Fig. 6.

Fig. 6: Reflection, Transmission in Snell's Law



Optical paths have different lengths. They have sequential reflections. Therefore, constructive interference will happen and transmission of filter will be maximum. If this condition does not hold, the interference between successive emerging rays will be destructive and the transmission will be relatively low (Wang, 2001).

Germanium (*Ge*)

Germanium has the highest index of refraction and it is used to infrared region. It can be use din any application in micrometer spectral regions. Thermal effect on its absorption and decreases it. butit will increase when value temperature is higher. Transmission of Germanium is normal upto 100°C. It suddenly decreases at a range 200°C to 300°C (Denton & Tomlin, 1972).

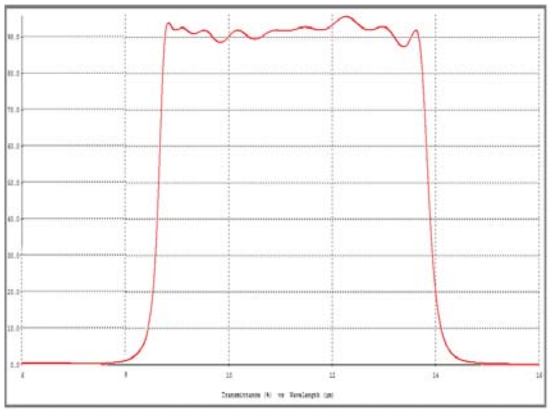
Silicon Dioxide (SiO_2)

In infrared systems often SiO_2 is used to achieve desired spectral region. Thin films are made of SiO_2 which has high homogeneity and good transmission in infrared range. Generally SiO_2 is used in optical filters for low index layer inside high index layers (Demiryont, (1985).

Results and Discussion

Infrared detectors need to be passed through a band pass filter. It deletes unwanted and annoying wavelength except infrared range. Optical thin film filters with this property need to be studied in case of its structure and factors influencing transmission spectrum. The structural factors such as layers material and their thickness as important parameters are in our focus. With attention to transmission and absorption coefficients, Germanium is selected for high index layer and Silicon Dioxide is selected for low index layer. Maximum transmission is produced by Germanium film with 196 nm thickness and Silicon Dioxide film with 451 nm thickness. Result of simulation proposed filter with software (TFCalc3.5) is shown that its transfer coefficient is more than 90% at range wavelength 8 µm to 14 µm. The characteristics transmission vs. wavelength is clearly seen in Fig. 7.

Fig. 7: Transmition vs. Wavelength for Proposed Optical Filter



Conclusion

Some infrared detectors are sensitive in a range of 8µm to 14µm and they can be able to detect humans under quake rubble after earthquakes. In this paper, an optical thin film filter is designed in this range and it improves there solutions and detection.

Advantage of the proposed Fabry-Perot filter as compared to previous thin film filter is that the material of film is cheaper than Ge/ZnS. The characteristic transmission is flatter than that of $a - s_i/ Al_2O_3$ filter. Number of layers and general thickness of filter is lower than Ge/MgF_2 filter.

References

Buser, R. G., & Tompsett, M. F. (1997). Uncooled infra-red imaging arrays and systems: Historical overview. *Semiconductors Semimetals*, 47, 1-14.

Chandran, A. (2001). *Self-Assembled Multilayered Dielectric Spectral Filters*. M. Sc.Thesis.

Christophersen, M., Kochergin, V., & Swinehart, P. (2004). *Porous Silicon Filters for Mid-to-Far IR Range*. Proceedings of SPIE, 5524.

Daleiden, J., Rangelov, V., Irmer, S., Römer, F., Strassner, M., & Prott, C. (2002). Record tuning range of InP-based multiple air-gap MOEMS filter. *Electronics Lett*er, 38, 1270-2002.

Demiryont, H. (1985). Optical properties of SiO2-TiO2 composite film. *Applied Optics,* 24(16), 2647-2650.

Epstein, L. I. (1952). The design of optical filters. *Journal of the Optical Society of the America*, 42(11), 806-808.

Denton, R. E., & Tomlin, S. G. (1972). Optical Properties of Thin Germanum Films. *Journal of Physics,* 8(25).

G. Corporation. Infrared parts manual. Retrieved from http://www.glolab.com/pirparts/infrared.html.

Haruyuki, E. (1999). Infrared sensor and infrared detector. *Ishizuka Electronics Corporation*

Herpin, A. (1947). Calcul du pouvoir reflecteur d'un systeme stratifie quelconque. *Computes Rendus*, 225, 182-183.

Hohlfeld, A., & Zappe, H. (2004). *A MEMS-based All-Dielectric Tunable Optical Filter with Increased Tuning Range*. Proceedings of SPIE, MEMS, MOEMS and Micromachining, 5455, 228-239.

Infrared. Retrieved from http://en.wikipedia.org/wiki/Infrared

Kakuta, N., Yokoyama, S., & Nakamura, M. (2001). *Estimation of Radio-active Heat Transfer Using a Geometric Human Model.* IEEE Transactions on Biomedical Engineering, 48, 334-331.

Komatsu, K., Mori, T., Sone, A., & Kimura, M. (1996). *Infrared sensor and method for production thereof.* United States Patent.

Liu, M. C., Lee, C. C., Liao, B. H., Kaneko, M., Nakahira, K., & Akano, Y. (2008). Fluoride antireflection coatings deposited at 193 nm. *Applied Optics,* 47(13), 214-218.

Liu, X., Cai, X., Qiao, J., Mao, J., & Jiang, N. (2003). The design of ZnS/Ag/ZnS transparent conductive multilayer films. *Thin Solid Films,* 441, 200-206.

Neumann, N., Ebermann, M., Hiller, K., & Kurth, S. (2007). Tunable infrared detector with integrated micro-machined Fabry-Perot filter. *Journal of Micro/Nanolithography, MEMS, and MOEM,* April-June, 7(2), 1-9.

P`erez, G., Bernal-Oliva, A. M., M´arquez, E., Gonza´lez-Leal, J. M., Morant, C., & Ge´nova, I. (2005). Optical and structural characterization of single and multilayer germanium/silicon monoxide systems. *Thin Solid Films*, 485, 274-283.

Planck, M. (1901). On the law of distribution of energy in the normal spectrum. *Annalen der Physik*, 4, 533.

Spitzer, V., Ackerman, M., Scherzinger, A., & Whitlock, D. (1996). The visible human male: A technical report. *Journal of the American Medical Informatics Association*, 3, 118-130.

Wang, J. (2001). A near infrared filter system and study solar umbral dots at 1.56 µm. M. Sc. Thesis, New Jersey Institute of Technology and Rutgers.

Zhao, Y., Mao, M., Horowitz, R., Majumdar, A., Varesi, J., Norton, P. (2002). Opto-mechanical un-cooled infrared imaging system: design, micro-fabrication and performance. *Journal of Micro Electro Mechanical System*, April, 11(2), 136-146.