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Insertion Layer in a Mid-Ir Band-Pass Filter Structure to Improve Optical Transmittance

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Abstract
Insertion of a single Ge layer deposition (denoted as layer *x*Ge) has been carried out to the band-pass filter structure to improve optical transmittance in a mid-IR region. The filter structure was of $Air/[Ge/ZnS]^N$ *xGe/Quartz* constructed from Ge/ZnS period layer deposition. From the modeling done, by introducing a layer period, $N = 10$, each layer thickness of Ge and ZnS prepared is 500 nm, the optical transmittance was found to improve significantly about 0.9 for *x*Ge = 0.80 (layer thickness of 80% of Ge thickness) compare than that of the greater value.
Keywords : band-pass filter, infrared, transmittance, Ge, ZnS

1. Introduction

An optical filter such band-pass filter as an optical component is widely used because of its characteristic able to transmit infrared (IR) radiation at a certain wavelength region and block the exclude region. For a certain application particularly in military technologies, an optical filter that operates at a mid-IR wavelength region at around 3-5 µm is considered to be very important as jet and rocket plumes produce radiation in that spectrum region (Mahulikar *et al*., 2009; Mahulikar *et al*., 2007). It is well-known that filter structure is prepared by introducing stacked layer materials of high and low refractive indices as a period layer. In an IR region, optical filter materials of Ge/ZnS have been used largely as this pair associates with high and low refractive indices, respectively. For a design of filter based on period layer deposition on the substrate, large number of layer pairs is needed to produce high transmittance of filter characteristics (Misra *et al*., 2004; Hawkins *et al*., 1998). Unfortunately, work to deposit large number of period layers leads some disadvantages such of time consuming, more complex layers, and inexpensive materials used. Therefore, many strategies have been carried out by researchers to improve a filter design to satisfy the characteristics required. The work has been done to modify the filter structure by introducing an additional period layer consists of three layer materials in a visible light spectrum (Misra *et al*., 2004, Asghar *et al.*, 2008) although they still have to introduce a great number of period layers. In this paper, we report the work to improve the optical transmittance by introducing an insertion single layer of Ge (denoted as *x*Ge) into the structure for a small number of period layers of Ge/ZnS deposition using a quartz substrate. The filter was prepared to meet its characteristic in the mid-IR region. The layer *x*Ge was inserted in the layer structure to introduce a relatively higher optical transmittance compare than that of the absence of this layer. This strategy is considerably interesting for a filter design to obtain a simple layer preparation of a filter structure that could guide the real fabrication of a band-pass filter component.

2. Theory and Modeling

Theory of optical transmittance and reflection for a filter usually refers to the matrix of light propagation through the layers (Misra *et al*., 2004; Bass, 1995). For an optical filter, the work of Macleod (2001) could be used as a reference that introduces combination of some period layers of thin film materials. If the media system consists of number of layers with different medium, the interface may exist in between these different media that will introduce any reflection and refraction phenomena. For multiple reflections through two different layers of *A* and *B*, the phase of electromagnetic wave when they propagate in these media could be expressed as $\delta_A = 2kn_A d_A \cos\theta_A / 2$ and $\delta_B = 2kn_B d_B \cos\theta_B / 2$, respectively (Misra *et al*., 2004). *k* is the wave vector of electromagnetic ($k = 4\pi / \lambda$), *n* is the refractive index of layer material, *d* is the layer thickness and θ is the angle of incidence. Subscripts *A* and *B* associate with the layer medium concerned. The matrix of wave propagation through two-component layers could be expressed as below (Misra, and Mishra, 2004).

$$M_{II} = M_A M_B = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix} \quad (1)$$

The matrix for propagation in layer *A* is written as

$$M_A = \begin{bmatrix} \cos\delta_A & i\sin\delta_A / n_A \\ n_A i\sin\delta_A & \cos\delta_A \end{bmatrix} \quad (2)$$

for layer B is

$$M_B = \begin{bmatrix} \cos\delta_B & i\sin\delta_B / n_B \\ n_B i\sin\delta_B & \cos\delta_B \end{bmatrix} \quad (3)$$

The transmission coefficient, t for a finite length of layered structure is

$$t = \frac{2p_0}{p_0 m_{11} + p_0 p_s m_{12} + m_{21} + p_s m_{22}} \quad (4)$$

where

$$p_0 = n_0^2 \cos\theta_0 \quad (5)$$

(for s-polarization state)

$$p_0 = n_0^2 / \cos\theta_0 \quad (6)$$

(for p-polarization state)

subscripts 0 and s are media for air and substrate, respectively. m_{11}, m_{12}, m_{21}, and m_{22} are matrix's elements of M_{II}.

From Eq. 1, relationship between transmittance and wavelength could be obtained. For radiation at a normal incidence, no difference of optical reflection property between s- and p-polarization states. As schematized diagram given in Figure 1, layers of Ge and ZnS associate with period layers of A and B, respectively. xGe indicates an insertion of layer deposition (percentage of layer thickness) of Ge material refers to Ge layer used at Ge/ZnS pair layer.

Refractive indices of Ge and ZnS used in the modeling refer to the work of Hawkins and Hunneman (2004), and Hawkins *et al*. (1998). For this work, we used a Mathcad software to find a relationship between transmittance and radiation wavelength of the filter. The temperature parameter used for the modeling is 295 K as at that temperature the refractive indices for both materials are constant over a mid IR region (Theocharous, 2005). From many reference works, the design of band-pass filter in the mid-IR region was usually prepared by introducing a large number of period layers of Ge/ZnS. This layer combination is used as a basic theory of band-pass filter design. The wavelength selection of optical transmittance is based on the constructive or destructive light interference. When the thickness of layers introduced into the structure and reflected light / radiation is in phase, light will pass through the layers, otherwise rejected. For modeling, layer structures of *Air/ [Ge/ZnS]^{10} xGe /Quartz* for x = 1.00, 0.95, 0.90, 0.85, 0.80, and 0 (no insertion layer), respectively have been introduced to study the transmittance of a certain wavelength spectrum in a mid-IR region at a normal incident angle (θ=0°). Ge and ZnS are high and low refractive indices, respectively used in the filter structure as a period layer. Each layer thickness of Ge and ZnS is varied for 475, 500 and 525 nm, respectively. By preparing a small number of period layers, N is 10, the filter characteristic of optical transmittance over the wavelength spectrum of mid-IR from about 3000 to 6000 nm will be investigated.

3. Results and Discussion

From the modeling done to the filter structure of *Air/ [Ge/ZnS]^{10} xGe /Quartz* including insertion layer xGe from 1.00 down to 0.80 for each layer thickness of Ge and ZnS is 500 nm, the results obtained are shown in Figure 2. Each transmittance curve is averaged from the data points obtained. The transmittance spectrum of the structure with no insertion layer xGe (x = 0) is given. The optical transmittance at a center of pass band is observed from around 0.55 to 0.90 From that figure, the number of oscillations or ripples arise associates with number of period layers. It has been observed that the increase number of period layers does not produce any qualitative improvement of the transmittance. The increase of period layers leads the increase number of oscillations due to the interference phenomenon experienced by light / wave. This increase does not reduce the ripples phenomenon. Efforts to reduce these ripples have been done by introducing some strategies by selecting the proper matching layer material between top and bottom layers of the configuration with an incident medium and the substrate, respectively but practically this work is not easy.

Another important point should be taken into account for a filter design is the value of optical transmittance that should be higher over the wavelength region. This point is important as the filter should have this characteristic and will be much interesting if the multilayers could be deposited using a simple layer preparation. For the above issue, in this model, insertion layer *x*Ge was introduced into the structure to improve the transmittance in a mid-IR region while the filter was prepared using a small number of layer periods to minimize cost and time consuming during the deposition. As we have investigated into the simple structure by inserting the layer, the decrease of *x*Ge layer thickness in the structure was found to increase the transmittance. This phenomenon shows us that multiple reflections in the multilayer structure tend to be in phase that leads to the constructive interferences. The ripples are still arisen due to a common phenomenon occurs when a quarter-wave thick layer of high and low refractive indices of material are introduced, but the matching layer material between the incident medium and substrate is considerably poor. From that figure, the bandwidth of transmittance over radiation wavelength region of 3250 to 5300 nm is observed to increase by the decrease of layer thickness. The cut-on and off patterns are found to be relatively sharp. The pass band is observed in the mid-IR region from around 3500 to 5000 nm. The curve of filter structure with no insertion layer *x*Ge exists in the structure is given, which the transmittance shows to be nearly similar to that for the structure with *x*Ge = 1.00. By comparing with the structure for $x = 0.80$, the filter structure consists of absence of insertion layer is found to be poor. This phenomenon shows that the insertion layer makes sense for the improvement of optical transmittance.

Modeling was also done to find a relationship between insertion layer *x*Ge and the center of transmittance spectrum by varying xGe layers (denoted as *x*) from 1.00 down to 0.80 as shown in Figure 3. From the curve, it is seen that the relationship tends to decrease linearly. This phenomenon shows us that the insertion layer $x = 0.80$ introduces a higher transmittance at a center of pass band spectrum compare than the greater value. At that insertion layer, the optical interference of multiple reflections inside the filter structure layers is considered to have an optimum condition due to the interference phenomenon is in phase may occur. Meanwhile, for the increase of insertion layer greater than that, it will be followed by the decrease of optical transmittance. This strategy by introducing an insertion layer into the structure could be assumed able to offer a simple technique to improve the transmittance of filter design.

By referring to the results obtained, it is convinced that insertion layer deposited on the bottom of the structure ($Air/[Ge/ZnS]^{10}xGe\ /Quartz$) has introduced a better result for its optical transmittance, however the characteristic is not similar when the insertion layer of *x*Ge deposited on the first layer of the structure ($Air/xGe/[Ge/ZnS]^{10}/Quartz$). This difference is shown in Figure 4 for $x = 0.80$ for each layer thickness of 500 nm. For the structure prepared by insertion layer on the top of layer deposition, the pass band is found to be much oscillating and the filter characteristic is poor. This is due to the light wave propagation that is not in phase. Meanwhile for the structure design by introducing layer deposition of insertion layer on the bottom of structure (on the substrate), the pass band is much better with more smooth spectrum compare than that of the other one. Modeling was also done to study the characteristic of pass band by varying the layer thicknesses of Ge/ZnS pair materials. As we can see in Figure 5, layer thickness of Ge is equal to ZnS of 475 nm, the cut-on pattern of curve starts to perform at a lower wavelength (3000 nm) compare than that of the thicker one (500 and 525 nm, respectively). However, the band width is considered constant at about 1500 nm. The maximum transmittance for all bands is found to be similar at about 0.90 at the center of band. The patterns of cut-on and -off of spectra are also observed to be similar.

4. Conclusion

From the modeling done to the filter structure of $Air/[Ge/ZnS]^{10}xGe/Quartz$ over mid-IR spectrum, the insertion layer *x*Ge shows much improvement for the optical transmittance at a center of pass band from around 0.55 to 0.90 for $x = 1.00$ down to 0.80. When the insertion layer *x*Ge is absence in the structure, the optical transmittance is found to be the same magnitude with that of the structure for $x = 1.00$. Much improvement of optical transmittance is observed for $x = 0.80$ introduced into the structure. The cut-on and -off patterns are observed to have relatively sharp for all values of insertion layer with a bandwidth for about 1500 nm. The insertion layer in the structure will change the characteristic of filter abruptly when that layer deposited on the top of layer structure (after air medium) rather than on the bottom layer on the substrate. For the structure of $Air/[Ge/ZnS]^{10}xGe/Quartz$, the increase of each layer thickness in a pair from 475 to 525 nm introduces pass band spectrum to move right to the greater wavelengths. This is because of the destructive interference phenomenon experienced in phase of multiple reflections in the multilayer structure. The shift of wavelength spectrum is due to the layer thickness of period layers.

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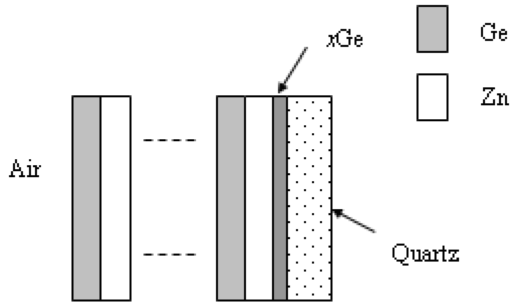

Figure 1 Schematized diagram of period layers (Ge and ZnS) in the structure.

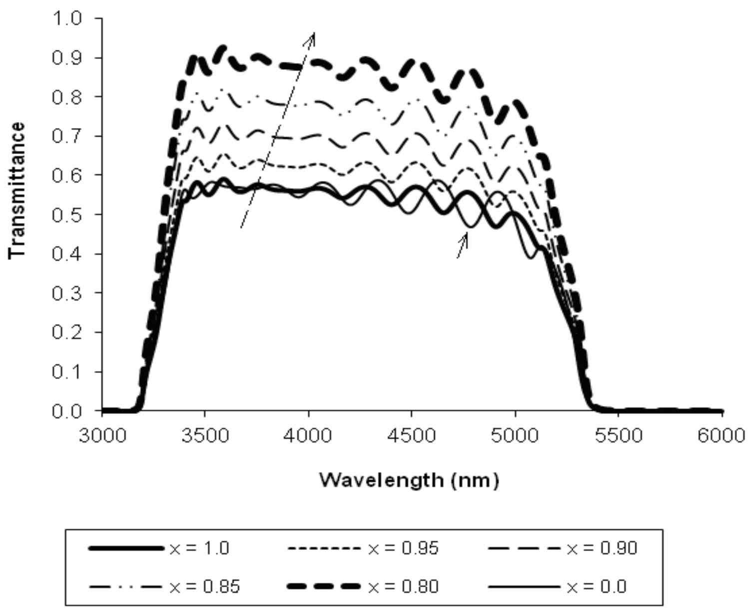

Figure 2 Calculated transmittance profiles of filter structure for decrease of *x* (guided by a dashed arrow). A solid arrow indicates the curve for filter structure with no insertion layer.

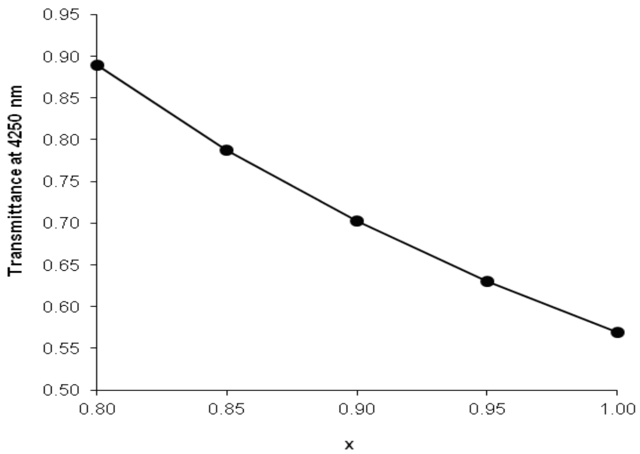

Figure 3 Relationship between insertion layer *x* and transmittance at the center of bandwidth spectrum (4250 nm) for filter structures for each layer thickness of Ge and ZnS is 500 nm.

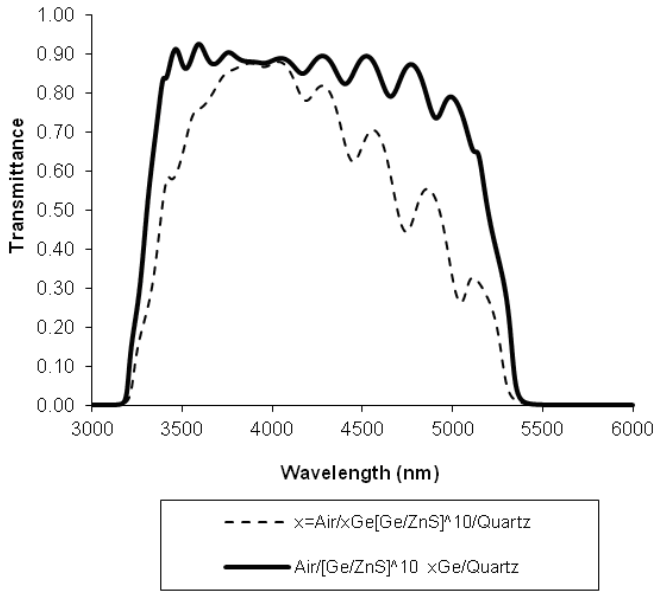

Figure 4 Comparison between calculated transmittance profiles for $x = 0.80$ of *Air/[Ge/ZnS]*^{10}*xGe/Quartz* and *Air/xGe [Ge/ZnS]*^{10}*/Quartz*.

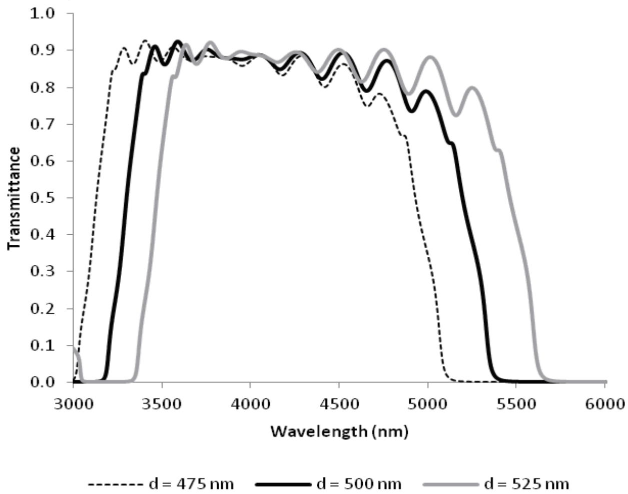

Figure 5 Bandwidth spectra of the structure *Air/[Ge/ZnS]*^{10} *0.80Ge/Quartz* for a variation of each layer thickness, d