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Design of Anti-Reflection Coatings for Application in the Infrared Region (10.6 micron)

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Abstract

In this research, anti-reflection coatings consisting of single and double layers were designed in the IR (8 – 14µm) region to reduce the unwanted reflections of germanium (Ge) substrate. The reflectance of Ge substrate was about 36% per surface. These values were reduced reasonably by using single and double layer anti-reflection. The used layers were promoted in their performance by changing their thickness and refractive indices. The results indicated that the suggested structures are very efficient in reducing the reflectance of the Ge substrates in the selected region. The performance of the double layer antireflection coatings of ZnSe, BaF_2 and BiF_3 on Ge substrates is presented.

Keywords: Antireflection coating; single and double layers, Ge substrates

تصميم طلاءات مضادة للانعكاس في المنطقة الطيفية تحت الحمراء (10.6 مايكرون)

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الخلاصه

هذا البحث ، تم تصميم طلاءات مضادة للانعكاس تتكون من طبقات مفردة ومزدوجة في المنطقة الطيفية تحت الحمراء µm (14 – 8) لتقليل الانعكاسات غير المرغوب فيها القاعدة من الجرمانيوم (Ge). انعكاسية الارضية غير المطلية حوالي (36 ٪) لكل سطح. يتم تقليل هذه القيم بشكل معقول باستخدام طبقة واحدة ومزدوجة مضادة للانعكاس. يتم تعزيز اداء الطبقات المستخدمة من خلال تغيير سمكها ومعاملات الانكسار. تشير النتائج إلى أن التراكيب المقترحة فعالة للغاية في تقليل الانعكاس على ارضيات الجرمانيوم في منطقة الاختيار. تم تقديم أداء الطلاءات المضادة للانعكاس للطبقة المزدوجة من ZnSe و BaF_2 و BiF_3 على الجرمانيوم.

1. Introduction

It is necessary to reduce unwanted reflections in optical systems [1]. This can be achieved by the use of anti-reflective materials as coatings, the production of which is currently comprising over half of the film coating industry. In addition, they have various uses which include glass lenses, lasers, mirrors, solar cells, narrow band-pass filters, multipurpose broad, and IR diodes, among others. Anti reflection coatings (ARCs) play a vital role in increasing transmittance and reducing reflectance. On optical surfaces, incident radiations are split into reflected, transmitted, absorbed and scattered fractions. ARCs depend on fractional or total cancellation of light reflected on both sides/surfaces of the film [2]. These films range from single layer to multilayer systems with more than 12 layers and

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virtually zero reflectance over a wide spectral range. The coating to be used for particular applications is dependent on wavelength, required performance, and cost, among many other factors to consider [3]. For the infrared region, germanium is mostly used as an optical component [4]. Single surface reflection causes a loss of 36% per surface of the incident light from such optical components, which increases the need for a largerquantity of such parts to be applied in creating the system. In this research, anti-reflection coatings consisting of single and double layers were designed in the IR (8 – 14μm) region for the reduction of unwanted reflections of germanium (Ge) substrate.

2. Theory

Both theoretically and experimentally, the simplest antireflection coating is a single layer which is commonly used in most practices [5]. Considering that n_0, n_1, and n_s represent the refractive index values of air, film, and substrate, the intensity of the reflected radiations at both surfaces of the coatings should be the same so as to repeal the two reflected rays. This implies that the ratio of the refractive indices at boundaries should be the same, that is [6]:

$n_0 / n_1 = n_1/ n_s$, or $n_1= (n_0 n_S)^{1/2}$ with film optical thickness, $n_1 d_1 = \lambda_o /4$,

where n_1 is the refractive index and d_1 is the geometry of the film. Only one minimum value in the reflectance region is given by this arrangement. A broader low-reflection spectral region is achieved with double layer interference anti-reflection coatings. The correct reflection coefficient at the boundaries is relied on by the two-layer coatings and the correct optical breadth of the layer, just like in single layer designs. This assists in obtaining destructive interference in the unwanted reflected radiation **[7]**. The following pairs of equations calculate the optical thickness for the two layers [8]:

$$\cos 2r_2 = \frac{2\left(1+n_1^2\right)n_2^2 n_3 - \left(n_1^2+n_2^2\right)\left(n_2^2+n_3^2\right)}{\left(n_2^2-n_3^2\right)\left(n_1^2-n_2^2\right)} \quad (1)$$

$$\cos 2r_1 = \frac{2n_1^2\left(n_2^2+n_3^2\right)-\left(1+n_1^2\right)\left(n_2^2+n_3^2\right)n_3}{n_3\left(1-n_1^2\right)\left(n_1^2-n_2^2\right)} \quad (2)$$

where $r_1=2\pi n_1 d_1/\lambda$; $r_2=2\pi n_2 d_2/\lambda$; n_1,n_2 and n_3 are refractive indices of first ,two layer

2.1 Multilayer matrix calculations

Abeles (1950) was the first to suggest the matrix technique of obtaining spectral coefficients of the structured media which have been applied ever since [9]. The transmittance and reflectance for multiple layer assembly on the substrate is determined by applying matrix calculations. For the case of a free multilayer design with normal incident radiations and homogenous optical films, the electric(E_{m-1}) and magnetic(H_{m-1}) fields at the boundary are related to the electric(E_m) and magnetic(H_m) field vectors and boundary of the neighboring film by the computation of matrices. The matrix is obtained as the size of magnetic field vectors and electric field vectors, considering also the layer properties [3]. The use of limits at each layer requires that the tangential sections of the electric and magnetic fields are not broken across layers to the calculations of wave movement. E and H field vectors that are moving in the direction of incident radiation are indicated by the "+" sign, while those moving against the direction are symbolized as "–". At the interface of m-th layer, the tangential components of the electric and magnetic fields are given as [10]:

$$E_m = E^{+}_m + E^{-}_m$$
$$H_m/H_1 = E_m/E_1$$
$$H_m = E_m \times H_1/E_1 \quad (3)$$

where E1 and H1 represent the tangential components of electric and magnetic fields at the interface between the film and the substrate. By ignoring the common phase factors, where E_m and H_m represent the resultants, then:

$$E^{+}_{m} = 1/2\left[\frac{H_m}{H_1 \big/ E_1} + E_m\right] \qquad \mathbf{(4)}$$

$$E^{-}_{m} = 1/2\left[-\frac{H_m}{H_1 \big/ E_1} + E_m\right] \qquad \mathbf{(5)}$$

$$H^{+}_{m} = 1/2\left[H_m + \frac{E_m H_1}{E_1}\right] \qquad \mathbf{(6)}$$

$$H^{-}_{m} = 1/2\left[H_m - \frac{E_m H_1}{E_1}\right] \qquad \mathbf{(7)}$$

The fields at another interface (m-1) are similar to those given by equations 4 -7, having the same of time and position with identical χ and y coordinates. These can be calculated by multiplying by phase thickness in Z direction, given by $e^{i\delta}$ or $e^{-i\delta}$, where [11]:

$$\delta = \frac{2\pi n_1 d_1}{\lambda} \qquad (8)$$

Thus, the E and H values across this interface are given by:

$$E^{+}_{m-1} = E^{+}_{m}\, e^{i\delta} = 1/2\left[\frac{H_m}{\eta_1} + E_m\right] e^{i\delta} \qquad (9)$$

$$E^{-}_{m-1} = E^{-}_{m}\, e^{-i\delta} = 1/2\left[-\frac{H_m}{\eta_1} + E_m\right] e^{-i\delta} \qquad (10)$$

$$H^{+}_{m-1} = H^{+}_{m}\, e^{i\delta} = 1/2\left[H_m + \eta_1 E_m\right] e^{i\delta} \qquad (11)$$

$$H^{-}_{m-1} = H^{-}_{m}\, e^{-i\delta} = 1/2\left[H_m - \eta_1 E_m\right] e^{-i\delta} \qquad (12)$$

where η_1 is the tilted optical admittance given by: $\eta_1 = H_1/E_1$

Now [12]:

$$E_{m-1} = E^{+}_{m-1} + E^{-}_{m-1} \qquad (13)$$

$$E_{m-1} = E_m \cos\delta + H_m \frac{i\sin\delta}{\eta_1} \qquad (14)$$

$$H_{m-1} = \eta_1 E_m\, i\sin\delta + H_m \cos\delta \qquad (15)$$

The equations above can be written in a matrix form as:

$$\begin{bmatrix} E_{m-1} \\ H_{m-1} \end{bmatrix} = \begin{bmatrix} \cos\delta & (i\sin\delta)/\eta_1 \\ i\eta_1 \sin\delta & \cos\delta \end{bmatrix} \begin{bmatrix} E_m \\ H_m \end{bmatrix} \qquad (16)$$

By solving the equation (16) above [10]. For the single-layer it can be expressed as the matrix as follows:

$$M_1 = \begin{bmatrix} A & iB \\ iC & D \end{bmatrix}$$

where $A = \cos\delta_m = D$, $B = i\sin\delta_m/\eta_m$, $C = i\sin\delta_m \eta_m$. For two consecutive layers, we have:

Layer 2 Layer 1

$$M = \begin{bmatrix} A_2 & iB_2 \\ iC_2 & D_2 \end{bmatrix} \begin{bmatrix} A_1 & iB_1 \\ iC_1 & D_1 \end{bmatrix} \qquad (17)$$

By multiply the two matrices, we have:

$$M=\begin{bmatrix} A_2A_1-B_2C_1 \\ iC_2A_1+D_2iC_1 \end{bmatrix}+\begin{bmatrix} A_2iB_1+iB_2D_1 \\ -C_2B_1+D_2D_1 \end{bmatrix} \quad (18)$$

Let $AA = A_2A_1 - B_2C_1$, $BB = A_2\, iB_1 + iB_2D_1$, $CC = iC_2A_1 + D_2\, iC_1$,
$DD = -C_2B_1 + D_2D_1$

The matrix can be written as:

$$M=\begin{bmatrix} AA & BB \\ CC & DD \end{bmatrix} \quad \textbf{(19)}$$

The multi-layer containing q-layers can be written as follows:

$$\begin{bmatrix} E_0 \\ H_0 \end{bmatrix}=\prod_{m=1}^{q} M_m \begin{bmatrix} E_q \\ H_q \end{bmatrix} \quad (20)$$

This multiplication matrix can be used to calculate the reflectance of a multilayered structure, as follows:

$$R_q=\frac{(n_0AA-n_SDD)^2+(n_0n_SBB-CC)^2}{(n_0AA+n_SDD)^2+(n_0n_SBB+CC)^2} \quad (21)$$

The reflectivity (R), transmittance (T) and absorbance (A) are linked by the equation: $R + T + A = 1$.

Solving of this matrix theoretically is a very difficult task for multiple layer coatings. Depending on the matrix theory, we use Math CAD bag to design and simulate the behavior of multiple layer coatings.

3. Proposed Design and discussion

Attenuated total reflection prisms are made from germanium which was found to have a very high refractive index. This material carries the potential to make a 50% beam splitter without the application of any other marerial. In addition, germanium is used as a component for the manufacturing of optical fibers. It carries all of the thermal band and is applied in lens systems for imaging. It can be coated with diamond to generate a very hard front optic [13]. Arcs of single or multiple layers are used to nullify reflective losses. Some few materials are available and applicable for use as antireflection coating materials. These include non-oxide chalcogenides (of varying compounds and compositions) and some fluorides. Among these, there is zinc selenide with an index of 2.4 [14] and a minute absorption coefficient. They also include barium fluoride which is transparent with 1.39 index, used in infrared applications and in thermography, as well as bismuth fluoride which is also transparent and has an index equal to 1.65 [8]. These materials are structurally stable and possess good adherence properties to germanium substrates [10,15].

A layer of zinc selenium/germanium Anti-reflective coating is initially designed/defined followed by multiple layers of Barium Fluoride/Zinc Selenide/Germanium and Bismuth Fluoride/Zinc selenide/Germanium. Zinc Selenide possesses an optical thickness that is 25% of the wavelength for the threshold reflectivity. This displays a reflectance of at least 3.25% in the 10.6µm range as is evident from Figure- 1. The aforementioned ARCs are considered in double layer designs in order to reduce reflectance. The refractive indices for

Germanium, Bismuth Fluoride, barium Fluoride and Zinc Selenide are 4.0,1.65,1.39 and 2.4, respectively [8, 14, 16].

The optical thicknesses for BaF_2/ZnSe/Ge systems for the layer are 1.701µm and 2.136µm, respectively, while those values for the combination with Bi instead of Ba

are 1.587 µm and 1.771 µm, respectively. Double layer coatings show a significant improvement in reflectance as compared to single layer coatings. In the 10-11 micrometers region, the reflectance is almost zero and both classes of coatings manifest the same values of reflectance, with a very slight change in the lower wavelength regions for the BiF_3/ZnSe/Ge system. Nonetheless, both of the coatings have values below 4% s of reflectance in the 8.7- 13.2-micrometer range.

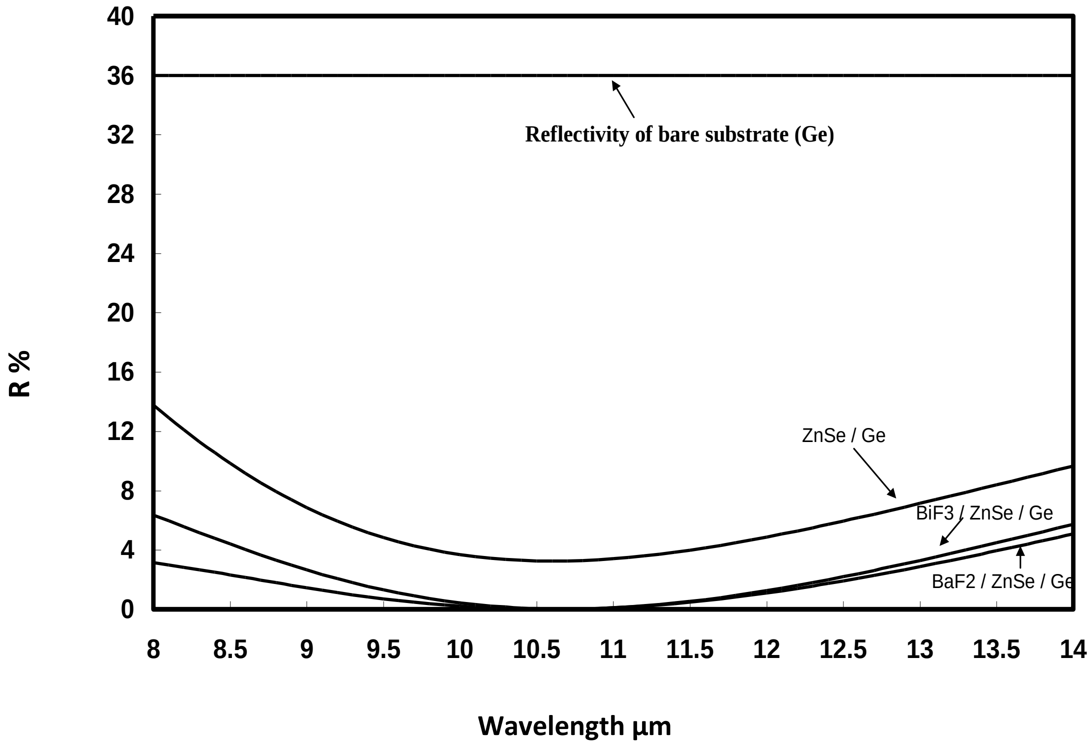

Figure 1- Reflectivity of single and double layer ARCs on germanium

BaF_2/Zinc Selenide/Germanium has a huge minimum across a range from 8-14 micrometers. The two coatings are the ideal ARCs in their specified region, and in the 8-14 micrometers region they are only considered as bandpass filters since the transmission is below 90%. The design data and reflectivity values for all of these designs are shown in Table- 1.

Table 1-Data and reflectivity values for all configurations on germanium

Configurations	Material	Refractive index (n) at 10.6 µm	Geometrical Thickness (nm)	R (%) at λ_o
Single layer	ZnSe	2.4 [14]	110.417	3.25
Double layer	BaF_2 ZnSe	1.39 [15] 2.4 [14]	122. 154 88.996	0.0033
	BiF_3 ZnSe	1.65 [8] 2.4 [14]	96.187 73.791	0.03

4. Conclusions

This design analysis reveals the that application of double layer anti-reflective coating systems, at determined refractive indices and thicknesses, can assist in reducing the maximum reflectance to very low values. These designs also express the great impact of thickness on reflectance.

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