WHY CAMERA LENSES APPEAR COLOURED ?

B.K. Sharma
Department of Education in Science and Mathematics
National Council of Educational Research and Training, New Delhi

The optical components, such as lenses, prisms and mirrors of a large variety of optical instruments (e.g. still/movie or TV cameras, binoculars, telescopes, microscopes, etc.) make use of the laws of reflection and refraction of light. The purpose of each of such instrument is to form as true an image as possible of the object. When a beam of light is incident on the boundary or interface between two media of different refractive indices (e.g. a glass plate/lens or a prism placed in air/liquid), a part of the light energy is transmitted, a part is absorbed and the remaining part is reflected from the surface. The transmitted or reflected light may form an image of the object if the light rays actually meet after transmission or reflection. The resulting image is often not distinct, on account of the stray light accompanying the transmitted or reflected light due to surface reflections.

The quality of a camera basically depends on ability of its lens system to transmit light through the glass. This ability depends on the surface area of the lens facing the object. In case of high quality movie or TV cameras, the optical system consists of multi-element lens system (a combination of several lenses), the light due to reflection from each of the refracting surfaces, reduces greatly the net transmission of light energy through it. In addition to lower transmission of light energy, the lens suffers from another drawback due to the surface reflections. The light reflected at the various surfaces may reach the focal plane of the camera in a random way here it gives rise to a 'ghost image', thereby reducing the contrast of the final image. In order to obtain a sharp picture/image, it is essential to reduce, by some means intensity losses due to the surface reflection of the camera lens.

Bloomed Lenses

Most of us might have noticed that the lenses of cameras, binoculars and other such high quality optical instruments appear to be coloured. The coloured appearance may vary from purple to blue-violet or even sometimes black, depending on the type and quality of optical system. Many of us might have wondered why the lenses made of transparent glasses should look coloured.

The coloured appearance of the lenses is due to thin film coatings on optical components (such as photographic camera lenses or microscope/ telescope objectives) to reduce/minimize loss of light due to reflection from the glass surface. Such a treatment by coating the surfaces of lenses with extremely thin films of a transparent material is highly effective in eliminating stray reflection of light and thereby increasing the contrast of the image formed by highly corrected lenses having a large number of air-glass surfaces. Such thin film optical coatings are called anti-reflection or non-reflective coatings. However, such non-reflective coatings destroy no light. There is no violation of the principle of conservation of energy in this process rather there is a redistribution of energy in manner that reduction in the reflected light intensity results in the enhancement in the intensity of transmitted light thus, these coating reduce surface reflection losses and improve efficiency of the lenses. The camera lenses look coloured because thin, transparent coatings of appropriate, durable material are applied on their surface. Such a coated lens appears as a 'ripe plum colour bloom' and so the lens is sometimes called 'bloomed' lens. It is for this reason that the camera lenses provided with such anti-reflection or non-reflective coatings are more popularly described as 'coated lens' or 'bloomed lens'.

Historical Background

The optical effects exhibited by thin films started playing key role, after having been motivated by the observations made by Fraunhoffer (1817) of enhanced transmission through the tarnished or tainted surface of a lens. Lord Rayleigh (1888) independently reported the lowering or reflectance from a tarnished plate made of crown glass and related it to the formation of a thin layer of refractive index different from that of the glass. H.D. Taylor (1891) also found that objects looked brighter through a tarnished telescope lens compared to that of a new one. Subsequently, Tayloe (1904) and Kollmorgen (1916) developed a chemical technique for artificially tarnishing a lens. Also G. Bauer (1934) showed that a thin transparent film coating on glass is able to increase the transmission of light energy, due to the interference of light reflected from the front and back surfaces of the film. With the development of such simple coatings called anti-reflection coatings and other thin film devices, a new field in optics, called 'thin film optics' came into existence and since then, tremendous developments in the field has taken place.

The optical coatings, in general, consist of dielectric layers stacked in the manner required by the design characteristics for a desired function. Such stacks may consist of single layer or multi-layer coatings. The effect produced by optical coatings is based on the phenomenon of interference of light. A beam of light entering the system of optical coatings suffers multiple internal reflections and the fractions of the incident beam that emerge as transmitted or reflected beam at the boundary of two media, acquire certain characteristics which are representative properties of the design pattern of the thin film stack. The simplest of such a design is a single layer of dielectric coating called the anti-reflection coating of single layer. Normally, the film thickness corresponds to 550 nm wavelength, in the yellow-green region of the visible spectrum, since the human eye is most sensitive for this wavelength. However, anti-reflection effects can be produced for any other wavelength by suitable controlling the thickness of the dielectric layers. The multi-layer system of anti-reflection coatings consisting of a stack of suitable high refractive index and low refractive index material of appropriate thickness, necessary to achieve better efficiency, having almost zero reflections over a wide wavelength range, has also been developed. The specific example of the anti-reflection coatings may be a pile of several glass plates (say 5 to 7) coated with the anti-reflection layer or film at the central portion of each surface. If such a 'coated pile of glass plates' is placed over any printed matter, the visibility of the printed matter through the coated portion of the glass gets considerably improved. The coated portion shows better legibility as compared to that through the uncoated portion because the transmission of light energy through the uncoated portion of the pile of glass plates is only about 60% or so.

Principle of Optical Coatings

The basic principle involved in the working of optical coatings is the phenomenon of interference of light. The phenomenon of redistribution of light energy due to superposition of two coherent light waves while travelling along the same direction in a medium is called interference. Due to superposition of waves from two such sources, at some points in a medium, the intensity of light is maximum at some points, depending on the optical path difference between them. The phenomenon of interference of light provides conclusive evidence that light behaves like wave rather than a stream of particles (as was believed by Newton). Light waves are electromagnetic waves and are transverse in nature. The light waves can even travel in vacuum with a speed, C, of 3×10^8 m/s and with a reduced speed v (=c/n) in an optically denser medium of refractive index n. The refractive index, n, of a medium varies with the wavelength λ of the light wave throughout the visible region (about 390 nm to 760 nm) in accordance with Cauchy's formula phase change of 180° or π rad $(n = A + B/\lambda^2 + C/\lambda^4 + \ldots\ldots$ The amount of bending of light wave at the interface of two media also varies with wavelength, giving rise to dispersion effects, such as that observed in case of a glass prism producing spectrum with white light.

When a light wave is incident on an interface separating two media (such as air and glass) and travels from an optically less dense medium (air) towards an optically more dense medium (such as a glass plate/lens), the reflected light wave undergoes a phase change of 180^0 or π rad. This rule is sometimes remembered using the phrase 'lows to high, a change of 'Pi'. When reflection occurs from an optically less dense medium (such as light incident from glass to air), the reflected light wave does not undergo such a phase change at the glass air interface. However, the transmitted light wave does not experience an additional phase change in either case.

Optical Interface Reflectance and Transmittance

The fraction of the light wave reflected from the interface separating two media increases with the angle or incidence and is determined by the refractive indices n_1 and n_2 of the two media. At grazing incidence (at angles of incidence, θ_1 nearly $90°$), the surface becomes an excellent reflector. A common example of this effect is the high reflecting power of a wet road when light from automobile headlights strikes the road with a grazing incidence. Even a clear window glass makes a reasonably good mirror when light strikes at a grazing angle. The fraction of the reflected light energy i.e., reflectance (or reflectivity) $R = I_r / I_0$) of an interface as a measure of the ratio of reflected irradiance I_r (or intensity proportional to the square of the amplitude of the reflected wave) to the incident irradiance/intensity I_0 and also the fraction of transmitted light energy i.e., transmittance (or transimitivity) T= (I_t / I_0) as a measure of the ratio of transmitted irradiance I_t (or intensity) to the incident irradiance I_0, are both determined by the refractive indices n_1, n_2 of the two media and the angle of incidence θ_1.The fraction (I_r/I_0) and (I_t/I_0) for glass (n=1.50) and air (n=1.00) for different values of angle of incidence at the air-glass interface for external reflection and internal reflection are shown in Fig.1(a) and 1(b) respectively. It may be observed that for angles less than the critical angle 41.8° (for a[illegible]s system) including normal incidence ($\theta_1 = 0^0$), part of the incident light energy is transmitted (Fig. 1a) an dpart is reflected (Fig.1b). As the critical angle ($\theta_1 = 41.8^0$) is approached, the transmitted fraction falls continuously to zero as shown in Fig. (1b) and for $\theta_1 \geq 41.8^0$ all the light energy is reflected.

The equations that describe the reflection and transmission of light at the boundary between two media are known as Fresnel's equations. These can be obtained by applying boundary conditions that require the continuity of the components of certain electric and magnetic fields associated with the propagation of light wave as an electromagnetic wave at the interface between two dielectric media.

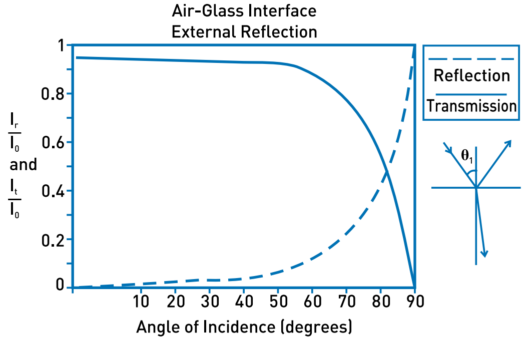

Fig. 1 (a)

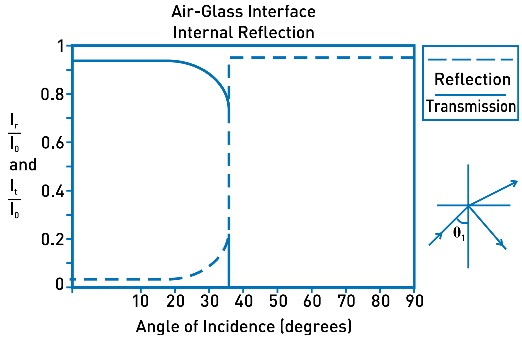

Fig. 1 (b)

Fig. 1(a) and (b) The fraction of light energy that is reflected at the boundary between the two dielectric depends on the angle of incidence. I_t and I_r are the transmitted and relected irradiances, respectively, and I_i is the incident irradiance. The fraction calculated here are for glass (n = 1.50) and air (n = 1.00)

Assuming absorption losses at the interface as negligible, the expressions for the reflectance — R(θ_1) and the transmittance T()at the interface can be expresses in terms of the refractive indices n_1, n_2 of the two media and the angle of incidence as (1,2)

$$R(\theta_1) = \frac{1}{2}\left[(n_1\cos\theta_1 - n_2\cos\theta_2)^2/(n_1\cos\theta_1 + n_2\cos\theta_2)^2 + (n_2\cos\theta_1 - n_1\cos\theta_2)^2/(n_2\cos\theta_1 + n_1\cos\theta_2)^2\right]$$

$$= \tfrac{1}{2}\sin^2(q_1 \square q_2)/\sin^2(q_1 + q_2)$$

$$+\tan^2(\theta_1 - \theta_2)/\tan^2(\theta_1 + \theta_2)$$

O r

$R(\theta_1) =$

$$\tfrac{1}{2}\Big[\Big\{\Big(n_1\cos\theta_1 - \sqrt{(n_2^2 - n_1^2 - \sin^2\theta_1)}\Big)\Big\}^2 \Big/ \Big\{\Big(n_1\cos\theta_1 + \sqrt{(n_2^2 - n_1^2 - \sin^2\theta_1)}\Big)\Big\}^2 + \{(n_2\cos\theta_1 - (n_1/n_2)\sqrt{(n_2^2 - n_1^2\sin^2\theta_1)})\}\Big/\Big(n_2\cos\theta_1 + (n_1/n_2)\sqrt{(n_2^2 - n_1^2\sin^2\theta_1)}\Big)^2\Big] \quad \ldots(1)$$

$T(\theta_1) =$

$$\tfrac{1}{2}\Big\{(4n_1n_2\cos\theta_1\cos\theta_2)/(n_1\cos\theta_1 + n_2\cos\theta_2)^2 + 4n_1n_2\cos\theta_1\cos\theta_2/(n_2\cos\theta_1 + n_1\cos\theta_2)^2\Big\}$$

$$- \tfrac{1}{2}\Big[\Big\{\Big(4n_1\cos\theta_1\sqrt{(n_2^2 - n_1^2 - \sin^2\theta_1)}\Big)\Big\} \Big/ \Big\{\Big(n_1\cos\theta_1 + \sqrt{(n_2^2 - n_1^2\sin^2\theta_1)}\Big)\Big\}^2 + \Big\{\Big(4n_1\cos\theta_1\sqrt{(n_2^2 - n_1^2 - \sin^2\theta_1)}\Big) \Big/ \Big(n_2\cos\theta_1 + (n_1/n_2)\sqrt{(n_2^2 - n_1^2\sin^2\theta_1)}\Big)\Big\}^2\Big] \quad \ldots(2)$$

where the transmitted light wave making an angle of refraction θ_2 with the interface normal follows the Snell's law of refraction as $n_1 \cos\theta_1 = n_2 \cos\theta_2$.

For normal incidence $\theta_1 = 0^\circ$ in either direction, equations (1) and (2) for the reflectance R and transmittance T reduce to

$$R = I_r/I_i = \{(n_2 - n_1)/(n_2 + n_1)\} \quad \ldots(1a)$$

$$T = I_t/I_i = \{(4n_1n_2)/(n_2 + n_1)^2\} \quad \ldots(2a).$$

Equations (1a) and (2a) may be employed to calculate the reflectance and transmittance of the interface separating two transparent media. It is interesting to note that for normal incidence, about 4% of the incident light is reflected at each interface or air-glass surface (n_1=1.00 and n_2= 1.50) of the eye glass/lens or a glass plate. Similarly, about 4.3% and 6% of the incident light is reflected at each interface or air-crown glass surface (n_1=1.00 and n_2= 1.52) and air-flint glass surface (n_1=1.00 and n_2= 1.65) respectively. Since the eyeglass or glass plate or lens has two boundaries the total amount of reflected light is about 8% of the incident light. Assuming that there is no absorption by glass, only 92% of the incident light energy striking the front surface of the eye glass/lenses is transmitted through the eye glass/lens and making it to the eyes.

The efficiency of a camera depend primarily on the transmittance of the lens. For a multi-element lens system having z glass-air boundaries (or interfaces), the transmittance can be expressed as

$$T = (1-R_1)\,(1-R_2)\,(1-R_3)\ldots\ldots(1-R_z)\ldots\ldots(3).$$

For a simple, single lens camera, despite its seemingly insignificance, this 8% reflectance (for the two surfaces of the lens, each contributing 4% reflectance) may actually seriously degrade the performance of the optical systems in two ways:

(i) When a large number of surface is involved, the transmission loss may be significant. For example, with a 4% reflectance at each glass-air surface, the net transmission is about 44.2% for a multi-element camera lens system (e.g. a typical 11 element camera lens) with 20 glass-air surfaces.

(ii) When the reflected light may also show up in undesirable places as a general haze or in the form of 'ghost images', thereby reducing the contrast of the image.

These major problems can be minimised or eliminated with the help of the anti-reflection coatings. As the reflectance R in equation (1a) is quadratic in the difference between the refractive index, the total reflectance may be reduced by interposing between the original two media a very thin film or layer of appropriate transparent material with an intermediate refractive index.

Anti-reflection Coatings

The unwanted reflections from the surface of glass lens or plate can be suppressed (at a chosen wavelength) by coating the glass surface of optional components with an appropriate material coating or film having suitable refractive index and of proper thickness. The performance of such thin film in anti-reflection coatings can be understood in a qualitative way by considering a parallel beam of light of incident intensity I_0, incident on the upper surface of the glass lens/plate of refractive index n_3 coated on one side with transparent thin film of thickness t and refractive index n_2, placed in air of refractive index n_1 (=1.00) as shown in Fig.2.

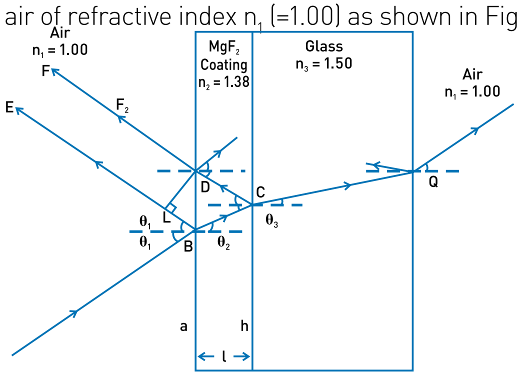

Fig. 2

In order to reduce reflectivity R, a material of appropriate thickness t and suitable refractive index n_2, chosen at some value ($n_1 < n_2 < n_3$) is deposited on the transparent substrate (glass). Then equal quantities of light will be reflected from the film's outer surface b (air-film boundary) and the film-glass boundary surface a, when a ray AB in incident, on the boundary of the air-film surface, making an angle θ_1 with the normal to it. At the interface a, it is partly reflected along BE as a ray r_1 from the upper surface of the film and is partly refracted along BC into the film with an angle of refraction θ_2 such that

$$\sin\theta_2 = (n_1/n_2)\sin\theta_1$$

At the point C, on the lower surface b of the film (or the film-glass interface b), the ray BC is again partly reflected firstly along CD, traversing as a ray r_2, and partly transmitted into the glass with angle of refraction θ_3 such that

$$\sin\theta_3 = (n_2/n_3)\sin\theta_2$$

and finally emerges out into the air. This emergent ray is parallel to the incident ray as the two surfaces of the film and the glass plate are parallel.

The incident beam thus gets divided at B into two beams of different amplitudes, out of which the refracted beam suffers multiple reflections and refractions at the interfaces a and b. The amplitudes of the reflected beams r_1 and r_2 from the air-film interface a and the film-glass interface b are nearly equal in magnitude but opposite in phase and hence these interfere destructively, depending on the optical path difference between them.

The optical path difference $\Delta = n_2(BC + CD) - n_1$ between reflected rays r_1 and r_2 is evidently

$$2n_2 t\cos\theta_1 = 2t\sqrt{(n_2^2 - n_1^2 - \sin^2\theta_1)}$$

and the phase difference λ between them $\Delta\theta$ between them = $(2\pi/\lambda) \times$ optical path difference

$$\Delta x = (2\pi/\lambda) \times 2t(n_2^2 - n_1^2 \sin^2\theta_1)^{1/2} \quad ....(4)$$

In case of a non-reflecting film, the light moves into a medium in which the velocity is less (denser medium) at each of the two reflecting surfaces, hence there is no resultant phase change due to reflection. By a judicious choice of the film thickness, we may easily establish destructive interference (and minimize the effect of reflection) between the light reflected at the lower and upper surfaces of the film for certain wavelength.

Quarter-waves Non-reflecting Film Thickness– A Necessity for Destructive Interference

Destructive interference occurs between the reflected rays r_1 and r_2, resulting in the minimum intensity, when optical path difference Δx between interfering beams is an odd multiple of half wavelength i.e., $(m+1/2)\lambda$, with integer $m=0, \pm 1, \pm 2, \pm 3, \ldots\ldots$, or phase difference Δ between them is $(2m+1)\pi$, being odd multiple of π. Thus, the condition for destructive interference in this case, using Eq.(4), is

$$2n_2 t\cos\theta_2 = 2t\sqrt{(n_2^2 - n_1^2\theta_1)} = (m + 1/2)\lambda \quad ...(5)$$

It may be noted that an additional, same phase change of π rad or 180°, on reflection, is associated with each interfering ray for reflection at both the upper and lower surface of the film coating. This is because the reflection is from the denser medium both at the air-film interface a and also at the film glass interface b. Since the same additional phase change occurs in each reflection, there is not net change in phase after the two reflections. This implies that Eq.(5) would be valid in this case as we seek destructive interference between the two rays i.e., r_1 and r_2 minimal reflection for a non-reflecting film coating so that maximum energy passes into the glass.

For normal incidence, the optical path difference for destructive inference, using eq.(5), leads to the expression

$$2n_2 t = \lambda/2 \quad ...(6)$$

Thus, maximum destructive interference occurs when the optical path lengths of the interfering beams r_1 and r_2 differ by half-wavelength. Consequently, no light is reflected and the film appears dark by reflected light. It follows from Eq. (6) that if the minimum film thickness $t = \lambda/4n_2$ is one-quarter wavelength for normal incidence, then the light reflected from the first boundary surface a (i.e. air-film interface), will be 180° out of phase with that reflected from the second boundary surface b (i.e., film-glass interface) and complete destructive interference will result. The minimum layer-thickness can be one-quarter wavelength for any given wave length.

Choice of Film Coating Material for Minimal Reflection

The minimal reflection (i.e., total cancellation of zero reflected intensity) can occur if the two reflected beams have the same intensity. Thus the condition for the reflectance R (or reflectivity) of a transparent material ensures that the reflected beams r_1 and r_2 have equal amplitudes/intensities, using Eq. (la) for normal incidence, can be written as R (air-film) = R (film-glass) Such that,

$\{(n_2 - n_1) / (n_2 + n_1)\}^2 = \{(n_3 - n_2) / (n_3 + n_2)\}^3$ ...(7)

Eg. (7) leads to the relationship amongst the refractive indices n_1, n_2 and n_3 as

$n_2 = (n_1 n_3)^{1/2}$ ...(8)

It follows from Eqs. (6) and (8) that the intensities of the two reflected beams are equal, when the refractive Index n_2 of the coated film/layer, of one- quarter wavelength thickness, for the normal incidence, is the geometric mean between those of the two media (i.e., glass and air). Consequently, the reflection will be divided equally between the two surfaces and complete destructive interference and minimum reflection would result.

This implies that a thin film of refractive index n_2, that is equivalent to the square root of the refractive index n_3 of glass (n_1 for air is 1.00), and of quarter wave optical thickness reduces the surface reflectance R of the glass to zero for a particular wavelength, say λ_0. This is usually chosen in the yellow-green region (λ_0 = 550 nm) of the visible spectrum for which the human eye is most sensitive. Ordinary window glass (n_3 = 1.50) can be rendered non-reflecting for yellow-green light (λ = 550 nm) by anti-reflection coating on glass with a thin film material of refractive index $n_2 = (n_2)^{1/2} = 1.225$ and minimum film thickness $t = \lambda/4n_2 = 112$ nm. In practice, suitable transparent, thin film material (solid substance) having a refractive index of 1.225 which satisfies the condition $n_2 = (n_1 n_3)^{1/2}$ with necessary harness are not available. A transparent and durable material such as magnesium fluoride (MgF_2) which has a refractive index of 1.38, close to this value, at wavelength λ = 550 nm in generally used as a compromise and can be readily deposited on the glass surface. In its natural form, it is called cryolite.

The reflectance of glass coated with a quarter wave thick film of MgF_2 having optional thickness of 100 nm at λ = 550 nm is reduced from about 4% to about 1% which is one-fourth that of uncoated glass. This can result in a considerable reduction in loss of light in the case of optical instruments. By using more layers, further reduction in reflectance or reflective intensity may be obtained, although the process is difficult and expensive. Fig. 3 shows how the significant reduction occurs in reflectance using two layers or three layers on glass lenses, in addition to single layer coatings. With such a single layer anti-reflection coating on all surfaces of the typical 11 element camera lens with 20 glass-air interfaces, the transmitivity increases from about 44.2% to 86%, for yellow-green light of the visible spectrum. Some reflection then takes place at both longer and shorter wavelengths and the reflected light has a purple hue.

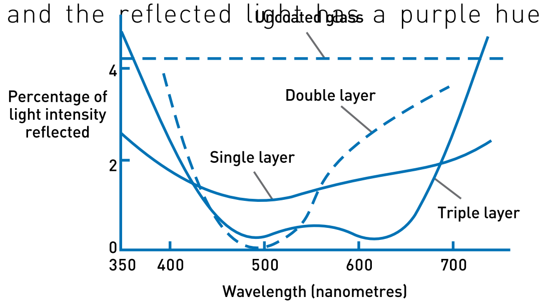

Fig. 3. Percentage of light intensity reflected by glass with one, two or three coating layers.

'Bloom' coloured Appearance of Camera Lenses

A glass lens (or a plate) coated with anti-reflection film looks bluish red (or purple) because the reflected light has predominantly blue and red components of visible white light. A single coating on a lens reduces the reflected light intensity to varying degrees throughout the visible spectral range of wavelengths. Such lenses specially designed for the camera are least reflective for a particular wavelength, usually for yellow-green light. They reflect more red and blue/violet light (at both longer and shorter wavelengths) which gives the camera lens a purplish red appearance. Thus the colour of the coating seen in the reflected light is (white minus green) magenta (i.e., a combination of red and blue light). This is the purplish red colour, which give the 'bloom' to the camera lenses.

More efficient anti-reflection coatings which give zero reflectance at a single wavelength or minimum reflectance over a wide range of wavelength region, can be designed by using multilayer anti-reflection coatings. However, the type of the anti-reflection coating in any desired, particular application will depend on a variety of factors including the type of the glass, the wavelength range, required performance and the cost factor. For example, binocular lenses and camera lenses, used in black and white photography, which have a few elements, need only single layer anti-reflection coatings. In cameras or other optical systems where monochromatic, coherent light such as Laser beam is used, two-layer anti-reflection coatings are ideally suitable which give zero reflectance at the required particular wavelength chosen for the purpose. However, in cameras used for true colour reproduction and those consisting of many element lenses, such as high quality camera lens that may have as many as 11 components or so, the lens surfaces should have at least three or more, multi-layer anti-reflection coatings to minimise the reflectance throughout the visible region. Glass lenses with this type of multi-layer coatings reflect very little or practically no light in the visible region and appear black.

Thus, by using two layers, one of higher refractive index and other of lower one, it is possible to obtain zero reflectance at one wavelength with available coating materials for anti-reflection coatings. More layers obviously afford greater latitude and more extensive possibilities. Therefore, with three suitably chosen layers, the reflectance can be reduced to zero for two wavelengths and can even be made to average less than (1/4%) over almost entire visible spectrum as shown in Fig. 3. In general, by increasing the number of layers, more efficient anti-reflection coatings can be designed. Alternately, the design performance of a few layer designs can be further improved. However, in practice, it is necessary to keep the number of layers to the minimum, on cost factor considerations and more particularly to avoid the possibility of errors and defects occurring in the coating process. Moreover, it may be remembered that the fewer the number of film coatings, the better is the optical performance of the anti-reflections coatings even at greater angles of incidence. When many element lenses coated surfaces are used, spectral variation of reflectance may significantly affect the character of the transmitted light. For example, spectral transmittance of 32 surfaces (3) of extra dense glass EDF-3(n=1.72) coated with MgF_2 anti-reflection film shows a transmittance of about 47% at 400nm, maximum peak transmittance of about 94% at 540 nm and then transmittance decreasing to about 64% at 700nm.

How to make Anti-reflection Coatings

The most versatile method of depositing the thin film anti-reflection coatings is the vacuum evaporation process. Almost all optical components of high-quality instruments are now coated with such films on the glass surfaces. It may be interesting to know how these thin films are deposited on the glass with only a brief description of making a single layer MgF_2 anti-reflection coatings, which are usually used for most camera lenses. These anti-reflection film coatings are deposited by evaporating magnesium fluoride on glass lenses in vacuum. The proper thickness depends on the time of exposure for 'the part to' these vapours. Clean glass lenses/components required to be coated are mounted on a spherical work holder. MgF_2 is put in a small molybdenum-boat and in mounted in between two electrodes provided on the base plate of the chamber. The chamber is evacuated to a high vacuum of the order of 10^{-5} mm of Hg and the material in the boat is heated to a very high temperature by passing high current through it (by resistance heating method). At high temperatures, MgF_2 evaporates and the vapours condense on the lens surfaces as thin film. While vaccum evaporation process is in progress, one of the glass surfaces is visually monitored for its reflected colour. The vacuum deposition process is continued till the coated glass starts showing the characteristic 'plum, purplish red colour' which corresponds to an optical thickness of a particular quarter-wavelength.

It may be mentioned that in various types of optical coatings the uniformity of deposit, with regard to thickness and structure, and accurate control of thickness amounting to integral multiples of quarter wavelength poses severe experimental difficulties. The uniformity of thickness and structure of optical coatings can be carried out by providing planetary rotation of the transparent substrates (glass surfaces) during the vacuum deposition process, wherein the rotation of each substrate about its own axis averages out the effect of varying angle of incidence. However, the rotation of all the substrates around the source averages out undesirable structural effects arising due to eccentric heating and non-circular shape of the evaporation source.

The thickness of the dielectric layers of appropriate transparent, durable substance is controlled by optical interference method. During the vacuum deposition process, a narrow beam of white light is allowed to be incident on monitor glass lens/plate on which the film is being deposited. The reflected and transmitted beam is then received on a photomultipliers tube after passing through an interference filter of the desired wavelength, usually for yellow-green colour of the visible spectrum, for which the optical coating is required. The intensities of the reflected or transmitted beams are complementary to each other due to interference effects, and the output of the photomultiplier tube shows intensity maxima or minima, corresponding to quarter-wave thicknesses. In order to make the optical method more efficient the incident monitor beam is chopped off at an appropriate frequency which eliminates stray light effects, especially that emitted from the vaporizing source material having been deposited in the form of thin film on the glass during vacuum deposition process.

References

COX, J. T. AND G. HASS. 1964. Physics of Thin Films. vol. 2. Academic Press, New York, USA.

CRUMMETT, W.P. and B. ARTHUR. 1994. Western, University Physics. Wm. C.BROWN. Communication Inc., USA.

GRANT, R. FOWLES. 1967. Introduction to Modern Optics. Holt, Rinehart and Winston Inc., New York, USA.

HOLLAND, L. 1966. Vaccum Deposition of Thin Films. Chapman and Hall Ltd., London.

LEO LAVI. 1968. Applied Optics, John Wiley and Sons, New York, USA.

MORTON M. STERNHEIM. AND JOSEPH W. KANE. 1986. General Physics. John Wiley and Sons, USA

RESNICK, ROBERT, DAVID HALLIDAY AND KENNETH S. KRANE. 1994. Physics. 8^{th} Edition, vol. 2. John Wiley and Sons, Singapore.