Module 1- Unit 1: Interference

Introduction

Interference of light is a typical wave phenomenon. We can explain the brightness and particularly darkness in the interference pattern on the basis of superposition principle obeyed by light waves. It says the resultant amplitude of two waves arriving at a point simultaneously is given by the vector sum of the individual amplitudes.

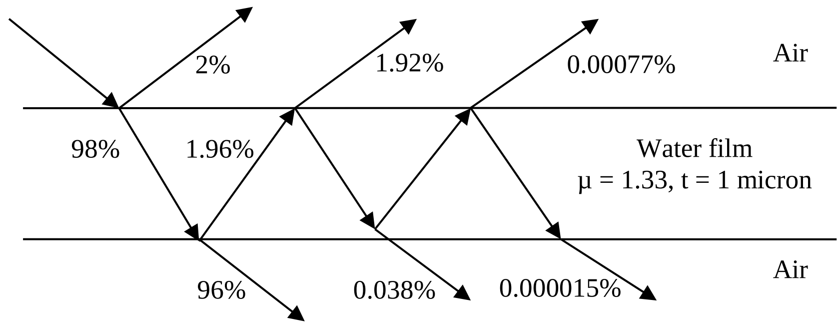
There are two ways to study interference: one, division of wave front in which, we consider that the incident wave front splits into two secondary wave fronts using pin-holes etc. and waves from these secondary wave fronts superimpose. Experiments like Young's Double slit or Lloyd's mirror are studied using this concept. Second, division of amplitude in which, we consider that the incident beam splits into two parts by partial reflection and transmission and these two parts superimpose on each other. Interference taking place in thin transparent film and Newton's rings are studied using the second concept. However, it is only a matter of practice and the Mathematics and Physics behind them is the same.

Examples of interference

In order to achieve a steady and well-defined interference pattern, we need to satisfy certain conditions like monochromatic and coherent sources, narrow and close slits or pinholes etc. Although such conditions are required in a strict sense, interference of light is not restricted only to laboratory and many interference effects can be observed in everyday life around us. Appearance of colours from a soap bubble, reflection of brilliant colours from oil films (particularly in rainy days), colours observed on the wings of a butterfly, holograms, sunglasses, optical filters, coatings on camera lenses and binoculars, spectacles with antiglare coatings etc. are in fact, examples of interference of light.

Thin transparent film of uniform thickness

There is no unique answer to what do you mean by "thin". It should be taken in a relative sense. As far as optics goes, by thin film we mean film whose thickness is comparable with the wavelength of light illuminating it. Films having thickness near to or at the most a few times the average wavelength of visible light can safely be called as "thin films". A film having thickness several times the wavelength is called "thick film". The thickness of a film plays the same role as that of separation between two coherent sources used in Young's double slit-like experiments. As the thickness of film increases, the coherence between the two interfering parts is lost and we do not obtain any interference pattern from thick films. Glass slabs for example, do not produce a clear interference pattern.



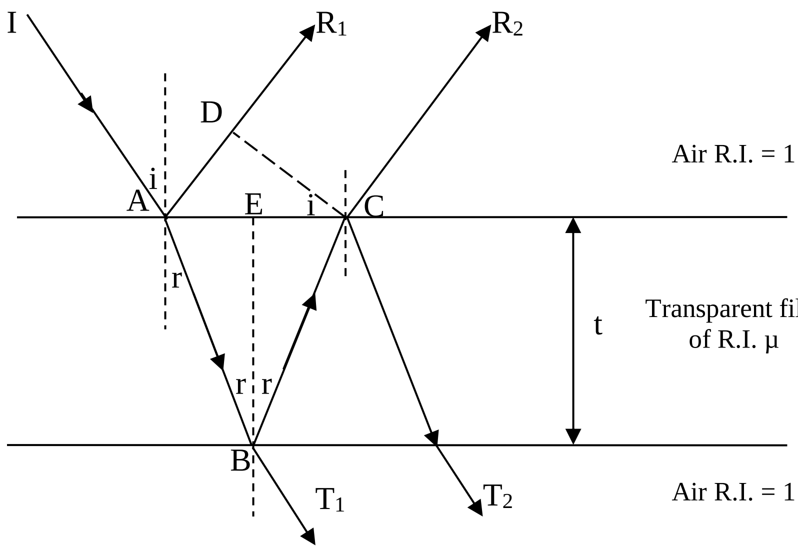
We consider a parallel beam of light incident on a thin transparent film of uniform thickness "t" and refractive index "μ". As shown in the figure, multiple reflections would take place. However, much of the incident light will get transmitted through the film. If we have a soap bubble for example, by taking the R.I. to be 1.33, the amount of light reflected is nearly 2%. A part of light passing through the water film gets reflected from the second boundary.

It can be seen that only the first two reflected parts have comparable intensity. The 3rd and higher reflections have negligible effect and we consider only the first two reflected rays for finding interference conditions. It can also be seen that interference of reflected light will be well defined since the two reflected parts have comparable intensity but the interference of transmitted light will be poor since the first transmitted part has much more higher intensity that the second transmitted part.

Interference in reflected light

Let "I" be the incident ray, R_1 and R_2 be the first and second reflected rays. As mentioned above, only the first two reflections are considered for interference. Let "i" and "r" be the angle of incidence and refraction respectively.

Ray R_1 undergoes phase reversal due to reflection from the surface of denser medium while ray R_2 does not undergo any phase change. Hence the net phase change is π.



The optical path difference between the interfering rays R_1 and R_2 is given by

$$\text{opd} = \mu(AB + BC) - AD \pm \frac{\lambda}{2}$$

We have multiplied the first term by R.I of the medium to get effective path covered by the ray R_2 since it travels in a medium with a slower speed as compared to R_1, which is moving through air. The time factor would be equal to the ratio of speed of light in air to the speed in the medium, which is nothing but the R.I. Further, the factor $\lambda/2$ arises due to the net phase change of π radian between R_1 and R_2.

Here, $AB = BC = \frac{t}{\cos r}$ and $AD = 2\mu t \frac{\sin^2 r}{\cos r}$.

Thus, the conditions of interference become

$2\mu t \cos r = (2n-1)\frac{\lambda}{2}$; Maxima or brightness

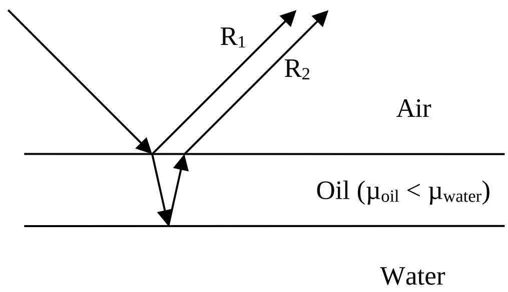
$2\mu t \cos r = n\lambda$; Minima or darkness

$n = 1, 2, 3 \ldots$

When the film is illuminated by monochromatic light, depending upon film thickness and angle of incidence, the condition of either constructive or destructive interference will be satisfied all-over the film. So, the film will appear bright or dark all over and we do not get interference bands as such.

When illuminated by white light, few colours get reflected constructively from the surface while few other colours are absent. The best example is that of colours formed on soap bubbles or soap films.

Note: If we have a configuration as shown in following figure, both the rays R_1 and R_2 would undergo phase reversal and the net phase reversal is 2π, which does not add any path difference.



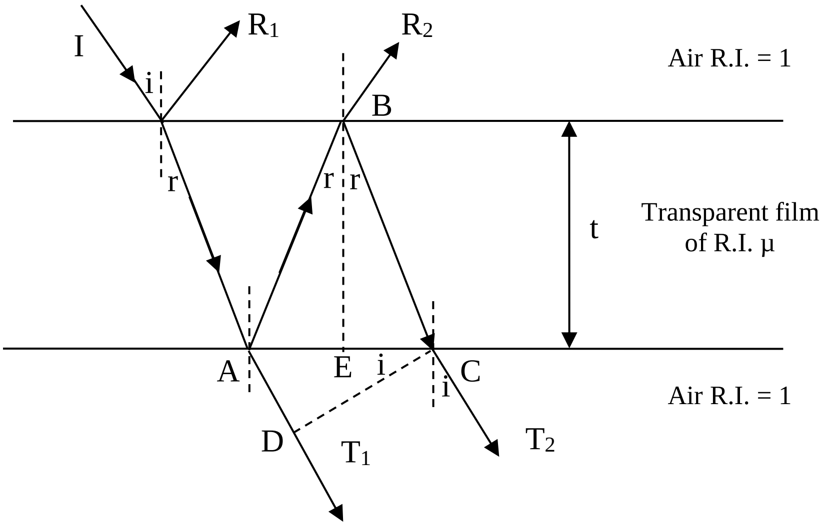
Here, the interference conditions would be complementary to above conditions.

Formation of colours

The condition for constructive interference for light reflected from a uniformly thin film is $2\mu t\cos r = (2n-1)\frac{\lambda}{2}$; $n = 1, 2, 3 \ldots$ White light consists of different wavelengths. If it is incident on a thin transparent film of uniform thickness, certain wavelength/s may satisfy the condition for constructive interference while some other wavelength/s may satisfy the condition for destructive interference for some fixed value of film thickness and angle of incidence. Colours (wavelengths) which satisfy the condition for constructive interference appear bright in the reflected light while colours (wavelengths) which satisfy the condition for destructive interference are cut-off from the reflected light. Therefore, the film appears to be coloured; the colour/s being that/those of the wavelength/s, which interfere constructively.

Interference in the transmitted light

For light transmitted from a thin transparent film of uniform thickness, waves are reflected from upper and lower surfaces of the film (internal reflections), which is a denser medium. Since both the reflections occur at the surface of air (rarer medium), there is no phase change and the factor $\lambda/2$ does not arise. Refer to the diagram.



So, in this case, the optical path difference is given by
$\text{opd} = \mu(AB + BC) - AD$
Note that the factor $\frac{\lambda}{2}$ is missing as there is no phase reversal. Due to this, the conditions of interference would be complementary to those obtained in the reflected light. They are given by,
$2\mu t\cos r = n\lambda$; Maxima or brightness
$2\mu t\cos r = (2n-1)\frac{\lambda}{2}$; Minima or darkness
$n = 1, 2, 3 \ldots$

Colours which are present in the reflected light are absent in the transmitted light

The interference conditions in the reflected light are given by,
$2\mu t\cos r = (2n-1)\frac{\lambda}{2}$; Maxima or brightness
$2\mu t\cos r = n\lambda$; Minima or darkness
Whereas the conditions in the transmitted light are given by,
$2\mu t\cos r = n\lambda$; Maxima or brightness
$2\mu t\cos r = (2n-1)\frac{\lambda}{2}$; Minima or darkness
$n = 1, 2, 3 \ldots$
From above conditions, it is clear that the interference conditions for the reflected light and transmitted light are complementary to each other. It implies that the colours, which interfere constructively on reflection, would interfere destructively on getting transmitted and vice versa. In short, colours present in the reflected light are absent from the transmitted light.

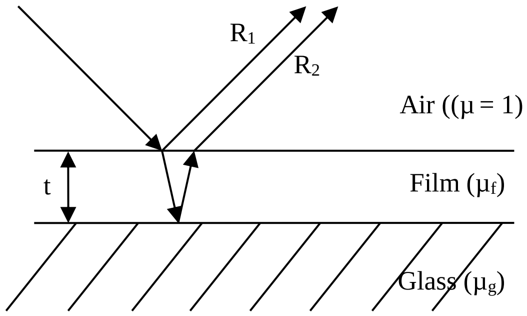
Anti-reflecting and anti-transmitting films

Interference involving multiple reflections (thin film, wedge shaped film, Newton's rings) has wide range of applications. Here, we will focus on application to anti-reflecting and anti-transmitting films.

Anti-reflecting films

- **Single layer film:**

The lenses used in optical instruments like telescopes, binoculars camera are often coated with a thin layer of transparent material like magnesium fluoride (MgF_2) or cryolite ($3NaF$, AlF_3) to avoid unwanted reflections as these reflection cause distortion in the image quality. Such films are called as anti-reflection films (ARF). The material coated has to satisfy two main requirements apart from basic requirements like good adhesion to glass, durability etc.



(a) Condition on refractive index: This condition says that the amplitudes of two rays R_1 and R_2 must be equal to obtain effective interference.

Amplitude of $R_1 = \left(\frac{\mu_f - 1}{\mu_f + 1}\right)^2$ and Amplitude of $R_2 = \left(\frac{\mu_g - \mu_f}{\mu_g + \mu_f}\right)^2$

The requirement $R_1 = R_2$ yields $\mu_f = \sqrt{\mu_g}$

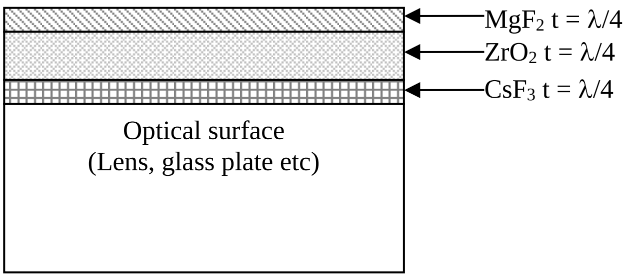
(b) Condition on thickness: This condition says that thickness of the film should be such that it gives rise to destructive interference of reflected light.

We have $\text{opd} = 2\mu_f t \cos r$. Assuming normal incidence, for destructive interference of rays R_1 and R_2,

$2\mu_f t = (2n - 1)\frac{\lambda}{2}$; n = 1, 2, 3...

$\Rightarrow t = \frac{\lambda}{4\mu_f}$

- **Multilayer films:**

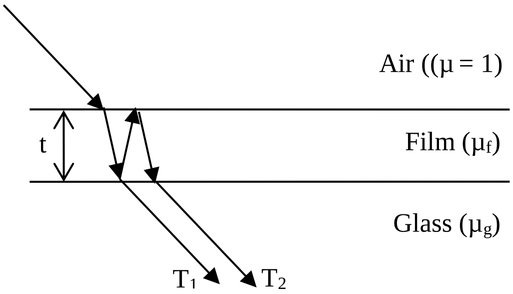


A single layer antireflection film is effective only at a certain wavelength and cannot totally reduce the reflection. Therefore, in practice, often multilayer films coatings are used. A three later coating system is widely used and effective over most of the visible spectrum coming from sunlight or lamps.

In this, the central layer is made of high R. I. medium such as zirconium dioxide, ZrO_2 ($\mu = 2.10$) and it has thickness = $\lambda/2$. The outermost layer is mostly of magnesium fluoride, MgF_2 ($\mu = 1.38$) and it has thickness = $\lambda/4$. The innermost layer is of medium having intermediate R.I. such as caesium fluoride,

CsF_3 (μ = 1.63) and it has thickness = $\lambda/4$. In some important applications like high resolution cameras or metallurgical microscopes, as many as 100 layered coatings are used.

Anti-transmitting films (single layer)



In some applications, it is desirable to have anti-transmitting films. Here also the glasses are coated with similar materials and their thickness is adjusted so as to avoid any transmission through the film. As before, the material coated has to satisfy two main requirements. One of them being that of refractive index which is covered in section 1.4.1 (a). The other condition viz. that of thickness is based upon formation of destructive interference in the transmitted light. For the air-film-lass combination described as above, the condition for minima in the transmitted light is given by,

$2\mu_f t \cos\theta = n\lambda$; n = 1, 2, 3...

Assuming normal incidence, the minimum film thickness for the film to act as anti-transmitting is given by, $t = \frac{\lambda}{2\mu_f}$.
