

Thin Film Optics

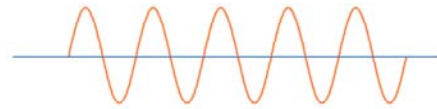
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Light

Light is a propagating disturbance characterized by an electric field and a magnetic field and so we describe it as electromagnetic. The fields are normal to the direction of propagation and they oscillate. We use the attribute *polarization* to describe their direction. At the very high frequencies of oscillation that characterize light (even infrared light) only the electric field has any significant interaction with materials and so we tend to think of the electric field when discussing the wave.

The linear nature of the interactions allows us to break our light into a spectrum of harmonic or monochromatic waves that we can examine separately. The variation of the electric and magnetic fields in such a wave is sinusoidal.



We usually use wavelength, the length corresponding to one cycle, to characterize the wave.

A light wave is a propagating electromagnetic disturbance. The electromagnetic nature of light was established by James Clerk Maxwell in the 19th century but already the wave nature had been established and interference was well understood.

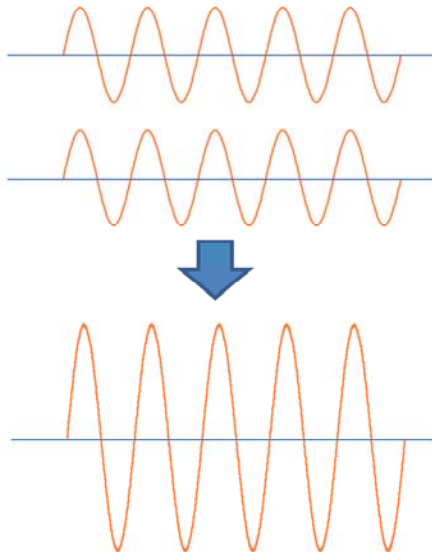
The effects we are interested in are linear. Linear means that if we have two separate stimuli and two separate responses then the response to the sum of the two stimuli will be the sum of the separate responses. The important implication is that we can then break any arbitrary light wave into a set of simpler components and follow them separately. Usually we will use a set of plane harmonic (or monochromatic) waves that we call the spectrum. Fourier theory allows us to do this theoretically but there are also all kinds of techniques that permit us to perform the decomposition experimentally. Each spectral element, or component, has a sinusoidal profile and can then be treated separately. We usually assume in our calculations a continuous spectrum of equal energy components and we do this more or less automatically without really thinking about it.

In linear media the frequency of the wave remains constant but traditionally we have always used wavelength to characterize the wave. Since the velocity varies with the medium, but is always constant in vacuo, the vacuum wavelength is used. Then the actual wavelength is λ/n where λ is the vacuum wavelength and n the refractive index.

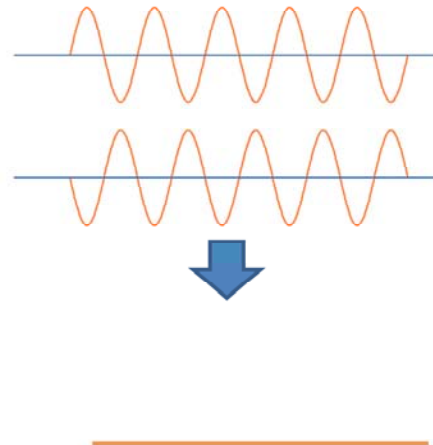
We use the term polarization to describe the direction of the electric and magnetic fields. Plane or linear polarization is most common and implies that the direction remains constant as the wave propagates – although, of course, it reverses during each half cycle of the oscillation. Polarization becomes important when we deal with coatings at oblique incidence.

Interference

Constructive interference



Destructive interference

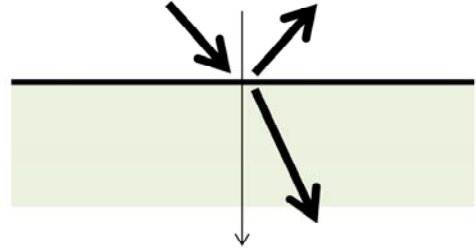


Interference is simply the addition of the fields of the various waves involved. If it involves two waves that are plane harmonic of identical frequency and polarization (that is the orientation of the fields) and are propagating in the same direction, then, if they are coincident in phase, the resultant amplitude is the sum of the individual amplitudes, and we call this constructive interference. If the fields are in antiphase, then the amplitudes subtract, and we call this destructive. These are the two extreme cases.

Optical Coatings

An optical surface rarely presents ideal optical behavior. Modifying the properties is the task of an optical coating and it is usually the specular properties that are of concern. We usually prefer that the surface figure be unaffected, but there is a limited class of coatings deliberately intended to alter the figure in desired ways.

Thin film optics is a huge subject permeating the whole of optics. Today, virtually every surface in any optical system exhibits properties assured by an optical coating. Metal layers in the form of mirror coatings came first, by about two thousand years. They rely primarily on the intrinsic optical properties of the metal. The behavior of dielectric, that is completely transparent, films is different. They are dominated by interference effects and they are the main subject of this talk.



Most optical systems consist, at least partly, of a series of optical surfaces formed in some suitable material. Their shape is chosen correctly to manipulate the light. However it is rare to find that the specular properties (mirror-like properties obeying the law of reflection and the law of refraction) that are determined by the optical properties of the medium and of the worked material, are acceptable. Modification of these properties is the primary function of an optical coating. However, since the coating is normally on the outside of the component it is often expected to perform other functions like limiting corrosion and increasing abrasion resistance. The coating usually consists of one or more thin films of material with composition and thickness chosen to give the correct optical properties through a mixture of interference and the natural optical properties of the materials.

Coating Manufacture



Optorun thermal evaporation machine.

The most usual techniques involve condensation from the vapor phase under vacuum.



Bühler Helios magnetron sputtering system



Shincron Radical Assisted Sputtering (RAS) machine

Coatings are usually manufactured by condensation of a suitable vapor under vacuum. The different processes vary in the way in which the vapor is produced. In thermal evaporation the material is heated until it boils or sublimates. In sputtering it is produced by bombarding a target by energetic ions. Machines are complex and expensive. Because of this cost, and because the coating process is often the final one for an already expensive component, yield is of great importance.

How it all Started



*The reverse side of a Celtic bronze mirror from Desborough, Northants, England.
Date: 50 BCE – 50 CE*

For a long time there were two completely separate threads. For many centuries practical coatings consisted of thin metal layers for mirrors. Then there were the curious colors in thin materials that had to wait very much longer before being either understood or usefully employed.



Photograph from Wikimedia Commons: Diesel spill on a road. Taken by Guinnog

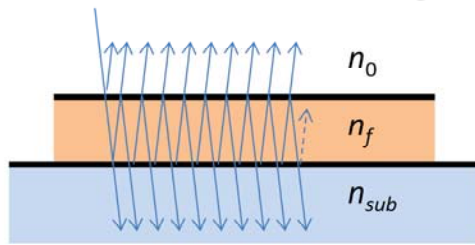
Mirrors were probably the earliest optical instruments. They existed all over the world and date back to prehistory. Lenses came a little later and, in the beginning, were used mainly as burning glasses. Interference colors were possibly recognized because there are many examples in nature, but the mechanism was neither known nor studied. The ancients divided materials into opaque materials that simply reflected, and materials that transmitted light to some extent.

Metals and Dielectrics (and Semiconductors)

Metals	Dielectrics	Semiconductors
Characterized by free electrons	Characterized by bound electrons	Characterized by bound electrons with a few free electrons
Electromagnetic radiation decays rapidly and exponentially.	Electromagnetic radiation propagates essentially freely	Electromagnetic radiation propagates essentially freely
Tendency to high reflectance	Tendency to high transmittance and exhibition of interference	Tendency to high transmittance and exhibition of interference

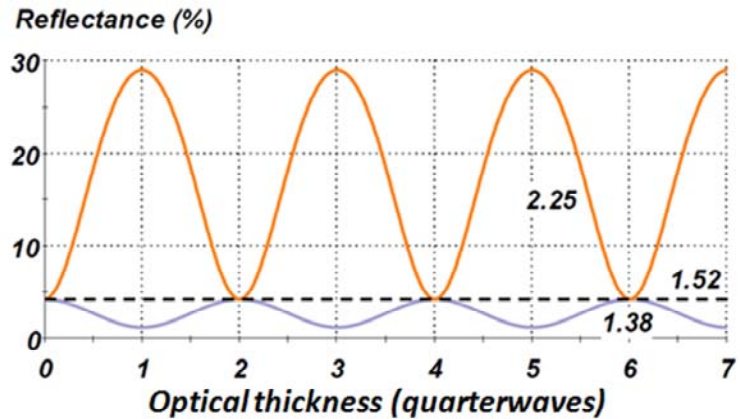
We usually classify our materials as metallic or dielectric. Metallic materials transmit little, unless very thin, and usually reflect quite strongly. Dielectric materials are essentially transparent. In thin film optics we will usually include semiconductors in the classification of dielectric. The transparent dielectrics support interference in thin films. The short-wave optical properties are dominated by electrons. The positively charged parts of molecules become important further into the infrared.

Interference in Thin Films



$$\text{Halfwave } R = \frac{(n_0 - n_{sub})^2}{(n_0 + n_{sub})^2}$$

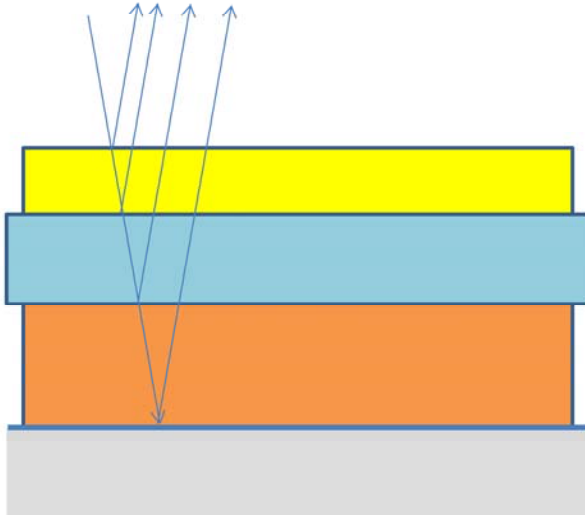
$$\text{Quarterwave } R = \frac{(n_0 - n_f^2/n_{sub})^2}{(n_0 + n_f^2/n_{sub})^2}$$



The materials are assumed to be without loss, i.e. dielectrics.

Imagine a dielectric substrate carrying a dielectric film in an incident medium also of dielectric material. The film will support multiple-beam interference as illustrated. Let the film be exceedingly thin so that the reflectance is exactly what we expect from an uncoated surface but the multiple beams still exist in the film and are adding up to that reflectance. Now let the thickness of the film be increased by one half wave. The first beam returning to the front surface now has an increase in its path of one wavelength and so the earlier phase condition is undisturbed. The next beam will acquire an extra two wavelengths and so on. It is easy to see that all the phase conditions are completely undisturbed. Since there is no loss, the interference condition is identical to that of the vanishingly thin layer so that a half wave thickness of material, or a whole number of half waves, yields the reflectance of the uncoated substrate. Halfway between the half waves, when the film is an odd number of quarter waves thick, the phase condition is perturbed to a maximum extent and so there is a significant change in reflectance. The formulae for reflectance in both cases are shown. They represent the extreme interference conditions. Other thicknesses give results in between these two limits.

Interference in Thin Film Multilayers

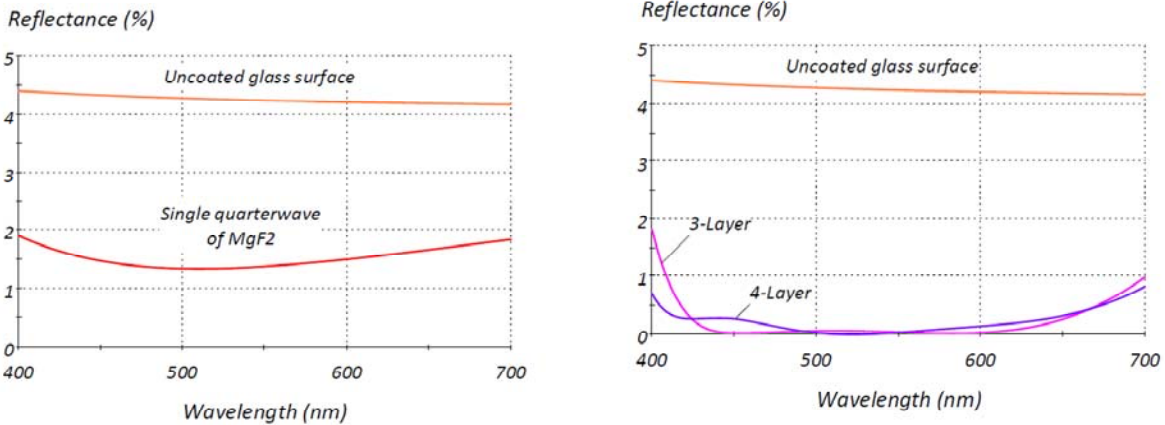


The principles are the same as single layers but the effects are much more complicated because there are many more light rays involved due to the reflections back and forth between the various interfaces. It is possible to organize the layers to produce a desired interference effect and thus to create optical coatings. Because quarterwaves and halfwaves represent extreme interference conditions and they are well understood we make much use of them.

Most optical coatings have more than one layer. Some have hundreds of layers. The interference calculations in such cases can be very complicated and are invariably carried out these days by computer. But it was not always so and much use is still made of quarterwave and halfwave films because they are straightforward to understand and they represent the extreme interference conditions.

Antireflection Coatings

The earliest dielectric coatings were antireflection coatings and they still represent a major coating production sector.



3-Layer: Air | QW MgF_2 – HW Ta_2O_5 – QW Al_2O_3 | Glass

4-Layer: Air | QW MgF_2 – HW Ta_2O_5 – $1/8$ MgF_2 – $1/8$ Ta_2O_5 | Glass

Simple optical surfaces reflect a portion of the light. This can be a problem because not only is the desired light reduced, but also the reflected light is not lost, but just goes somewhere else. Somewhere else can often be the image plane, where it causes ghost images and veiling glare. Most simple optical surfaces, therefore, are treated with an antireflection coating. The least complex is a quarterwave of magnesium fluoride that reduces the reflectance of glass as shown. Ideally we would like a material of still lower index but magnesium fluoride is the best we have. In very simple systems this single layer can often be enough and so this coating is still produced on an enormous scale. However more demanding systems require better performance and two common multilayer coatings are also shown. The four-layer one is usually preferred because it uses two materials only. In practice the layer thicknesses in the four-layer are adjusted very slightly from the values shown to optimize the performance. These coatings are intended for the visible region, 400nm to 700nm. Antireflection coatings are required and manufactured over the whole optical spectrum. The greater the region over which reflection reduction is required, the more complex and difficult the design and the manufacture, and so the region of best performance is invariably limited to some extent.

Antireflection Coating

Here we have an antireflection coating that has been placed on both sides of the glass in the form of the logo of a major ophthalmic company located in Barcelona. Now the uniformity of the layers over the coated surface becomes important.



Particularly in Europe and in Asia, spectacle lenses are usually antireflected. This reduces glare, especially in night driving, but also avoids the flare that is often seen from uncoated spectacles and masks the eyes in a photograph. Such effects become still more acute with the high index plastic lenses, like polycarbonate, that are gradually replacing the lower index materials. The usage in the United States is increasing, but is still lagging behind other regions in uptake. Here we have a demonstration of an antireflection coating on a blank lens, but, so that the performance can be readily gauged, limited in its coverage to the logo of the company that produced it. There is some residual color that, strictly speaking, is a performance defect but is presented by ophthalmic companies as a feature. The color has become an important fashion statement that is actually strongly desired by the customer.

Antireflection Coating

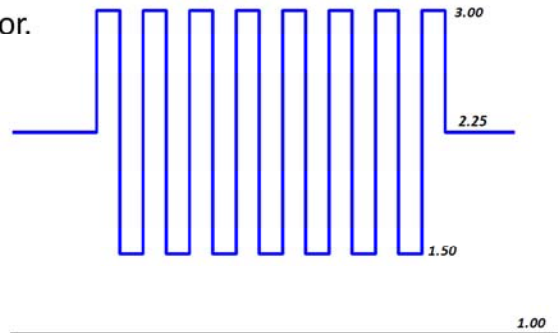
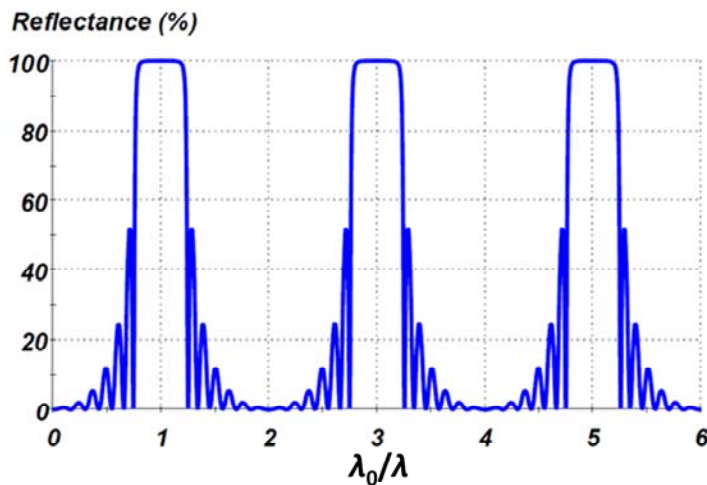
A popular antireflection coating is the ruby coating often seen on binoculars. The ruby coating deliberately reflects part of the red region and actually narrows the transmitted spectrum. This reduces the chromatic aberration of the optical system and so eases the performance requirements for the optical system. Cameras and high-end binoculars normally use a broader coating.



Here we have an antireflection coating on the objectives of a binocular telescope. This particular coating is known as a ruby coating and in display units in stores there is often a spotlight to illuminate the coating that then appears to glow and look very powerful. The ruby color is produced intentionally in the design that is actually more complicated than a simple antireflection coating. It is applied for two main reasons. One is connected with sales, because the ruby coating seems more scientific and impressive than a less colorful one. Another is that the spectral range is reduced and so the requirements on chromatic aberration relaxed. High-end binoculars have a broader and less spectacular coating as do better camera lenses.

The Quarterwave Stack

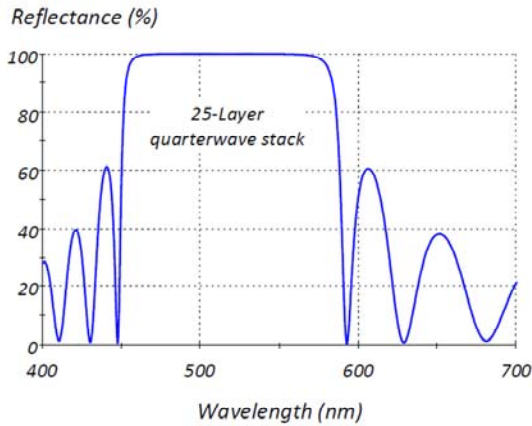
The quarterwave stack is our basic dielectric reflector.



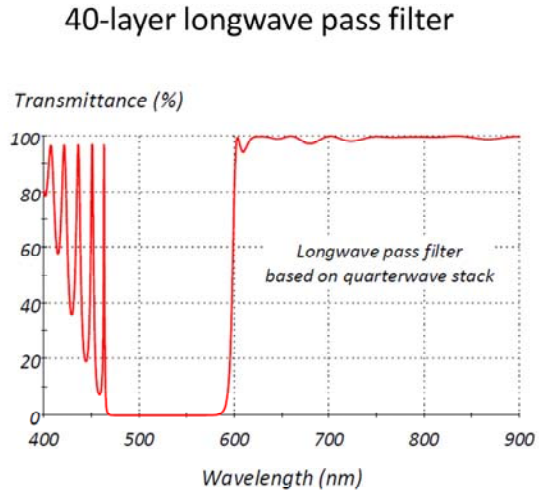
It also acts as the basis for edge filters, notch filters, dichroics, and narrowband filters.

Although high performance metals reflect strongly they still have significant absorption losses and many applications require higher performance. We can achieve exceedingly high reflectance over a limited region using a stack of quarterwaves of alternate high and low index. At the wavelength for which the layers are exact quarterwaves, all the multiple beams emerging from the top surface to form the reflected beam are exactly in phase, and the interference is maximum constructive. The width of the high reflectance zone is restricted and the higher the ratio of high to low index the broader is the region, but it is always rather restricted. Obviously at one half of the design wavelength the layers become halfwaves and their interference effects vanish. The high reflectance repeats at one third and one fifth, and so on, of the fundamental wavelength. Laser mirrors are commonly of this design. The horizontal scale in this diagram is normalized so that the performance details can easily be seen. The next slide shows a more usual plot.

Uses of the Quarterwave Stack



Basic low-loss reflector



Here we plot the characteristic of a typical quarterwave stack in the visible region as a function of wavelength. It covers only part of the region. By using more layers and staggering their thicknesses we can extend the width to cover the whole of the visible but for really wide high-reflectance coatings we still must make use of metal layers especially aluminum.

The characteristic curve on the right is of a longwave pass filter based on the quarterwave stack. Longwave pass and shortwave pass are commonly referred to as edge filters. The residual fringes outside the main reflecting region are usually referred to as ripple and the ripple can be reduced by a process of matching which is not unlike the addition of an antireflection coating but of more complicated design and invariably the product of an automatic computer process. The big advantage of the interference edge filter is that it can be positioned at will simply by altering the thicknesses of all the films in the same ratio.

If the edge filter is used as a beam splitter to separate two spectral regions then it is referred to as a dichroic beam splitter (even if its performance is in the infrared or ultraviolet).

Color Separation Filters

All kinds of filters can be designed and manufactured. Here we have some sets of color separation filters. The colors are purely the result of interference. These are reflected colors. Those in transmission are complementary.



Here are some color separation filters that are based in their design on the quarterwave stack but with the ripple-reducing additions. The colors shown are in reflection and, since there is no loss, the colors in transmission will be complementary. Thus the top row shows subtractive primary colors but those in transmission will be additive, and vice versa for the lower three.

Cavity Structures

Air | HLHLHLH LLLL HLHLHLH L HLHLHLH LLLL HLHLHLH | Glass



Cavity

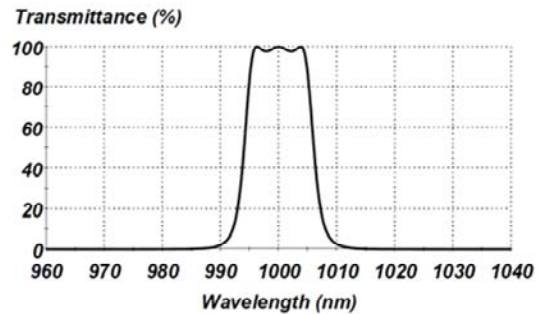
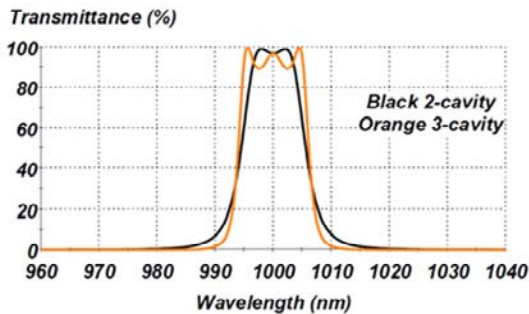


Coupling Layer



Cavity

Adjusting the number of halfwaves in the cavities and the number of layers in the reflectors gives a fine-coarse control over the bandwidth.

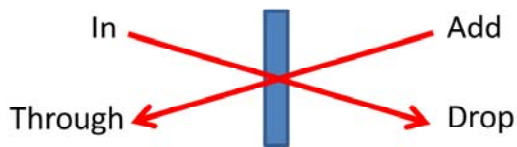


Increasing the number of cavities steepens the sides but often introduces larger ripple.

Here a simple two-layer match next to the air incident medium has reduced the ripple.

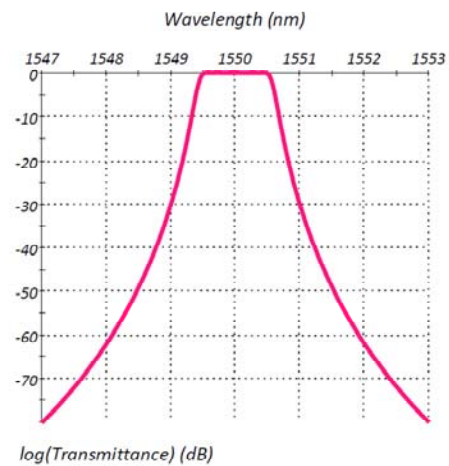
A halfwave, or multiple halfwave, layer surrounded by two equal quarterwave stacks, yields what we call a tuned cavity. It has the property of high transmittance at the reference wavelength, where the layers are halfwaves or quarterwaves, and high reflectance elsewhere. Thus it acts in transmission as a narrowband filter. The sides of the passband can be steepened by adding further cavity structures as shown. Such filters are used in an enormous range of applications in the ultraviolet, visible and infrared. The design principles are the same in all regions but the useful materials differ. The design notation used here is a common one where a quarterwave layer is indicated by a capital letter. If there are only two materials an H for a high-index quarterwave layer and L for a low index are common symbols. LLLL then indicates a thickness of four quarterwaves of low index, or one full wave, and can also be written as 4L.

Multiplexing and demultiplexing filters for telecom



Optical signal channels that have wavelength coinciding with the passband of the filter are dropped or added while all others are reflected.

This filter has 158 layers of silica and tantalum but telecom filters can have as many as 300 or more. This filter has 158 layers. The two fractional thickness layers in front are matching layers to reduce ripple.

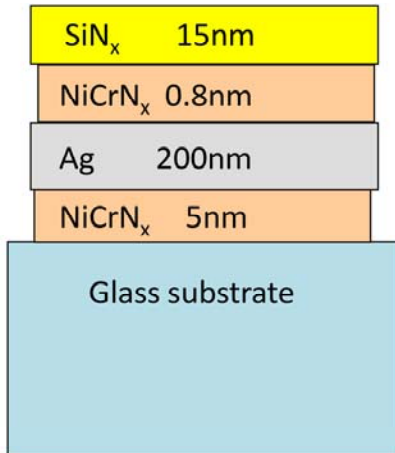


Air | 1.267L 0.338H (HL)⁷ H (HL)¹⁵ H (HLLH (HL)¹⁵ H HLLH)² (HL)¹⁵ H (HL)⁷ H | Glass

An important application for multiple-cavity narrowband filters is in multiplexing and demultiplexing of the optical channels in optical fiber communication. We can think of the component as a four-port device. The signal at the in port consists of many equally-spaced channels. All of these, with the exception of the chosen channel at the filter peak, are reflected to the through port. The chosen channel continues through the filter to the drop port. A replacement channel at the same frequency can be added to the others through the add port. Because of the exceedingly tight requirements on leakage between the add and drop channels, what is called coherent crosstalk, the full four port configuration is rare. Usually it is limited to three ports. The use of two three-port configurations satisfactorily reduces the coherent crosstalk. The design and production of such filters is an exacting task and specially designed coating machines are used. To make the design notation more compact we write repeated structures as (HL)⁷ or (HL)⁷ which indicates that the structure within the brackets is repeated seven times.

Silver-Based Telescope Mirror Coating

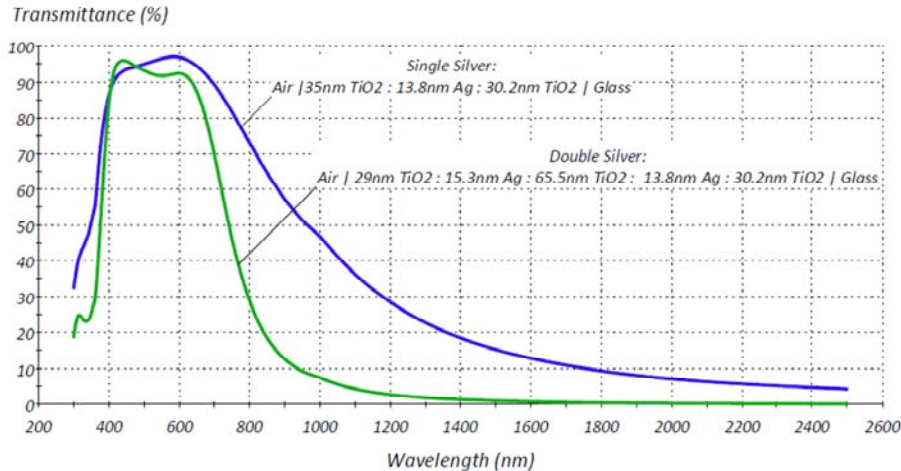
This is one of the Gemini primaries coated in a special vacuum chamber where linear magnetron sources rotating about the mirror center cover it in three passes with uniformity errors less than 1nm.



Courtesy Gemini Observatory

Aluminum replaced silver as the coating of choice for astronomical telescopes in the 1930's. In a curious reversal, silver is making a comeback. The reason is largely in the infrared. Silver has a higher reflectance than aluminum (silver has the highest reflectance of all metals) and so its emissivity is lower. The emittance of the mirror surfaces is the major limitation to the detectable weakness of infrared sources. Unfortunately silver is much less environmentally resistant than aluminum and so must be protected by the surrounding nitride films that render the production of the coating much more demanding than simple aluminizing. There are two Gemini telescopes, one in Hawaii and one in Chile and together they cover the entire sky. Their primary mirrors are 8.1 metres in diameter. A linear magnetron source is a special kind of sputtering source.

Low E Glass - Energy Saving Glazing

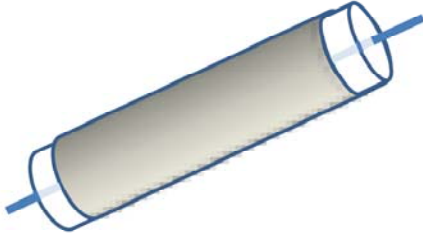


A correctly chosen high index thin film of the correct thickness can reduce the reflectance of a thin silver layer virtually to zero. This is the principle of the low E glass. The effect of the dielectric disappears at longer wavelengths and the reflectance rises.

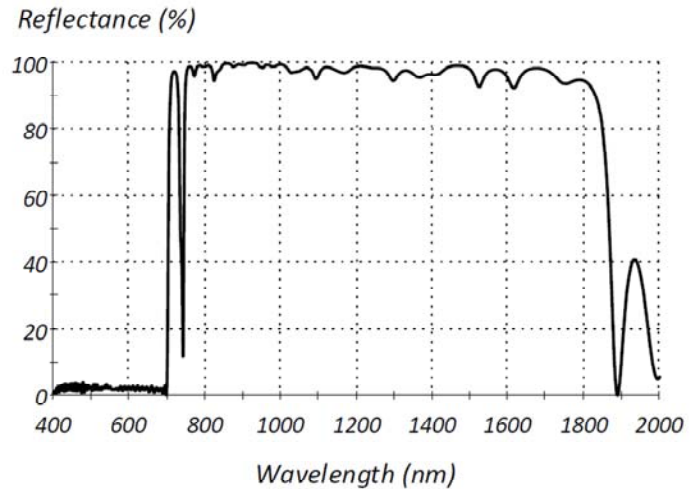
Heat loss in the winter and heat gain in the summer through glazing puts considerable strain on building temperature control systems and can be costly. Most advanced countries have regulations that require the use of energy-saving glazing in the construction of public buildings. The coatings, in terms of the number of layers, are simple, but their production is exacting and there are strict specifications on color and throughput. Different colors are available, but architectural and aesthetic considerations demand that it does not vary perceptibly in any single building. The coatings are based on silver. It is possible to antireflect thin silver layers so that they transmit well in the visible region but reflect strongly in the infrared where the antireflection performance falls off. The global demand for low-E coating is currently estimated to be in excess of 1 billion square metres per annum. The lists of layers in the designs omit the very thin diffusion barrier layers that are inserted on either side of the silver layers. They usually consist of a nanometre or so of active metal that is allowed to oxidize in situ. Nickel, titanium, chromium are typical metals used for this.

Energy-Efficient Halogen Floodlights

Although LED lighting is gaining ground, halogen floodlights are still produced and used. Gains of a factor of two or more in efficiency are possible by redirecting the infrared content of the output to the filament by a coating on the outside of the envelope.

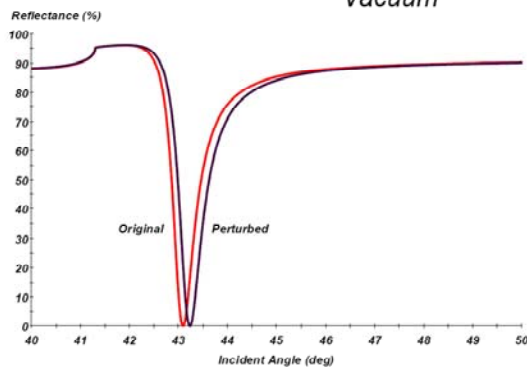
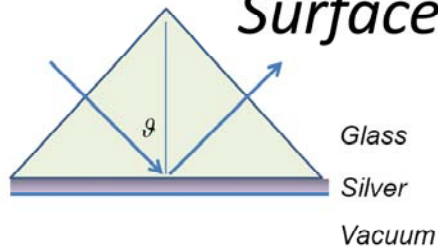


This high-performance filter has 100 layers. Not all coatings are as efficient or have as many layers.



All kinds of different coatings are combined with light sources. Some are for color correction, especially to render light more like daylight. Here is an example of a coating that increases the efficiency of a filament-based lamp by directing the heat content back to the filament. Although the silver-based coatings shown earlier present useful characteristics they do not have sufficient resistance to the high temperatures of the lamp envelopes and so the lamp coatings have to be based on refractory dielectric materials. The designs are therefore much more involved.

Surface Plasmon Resonance



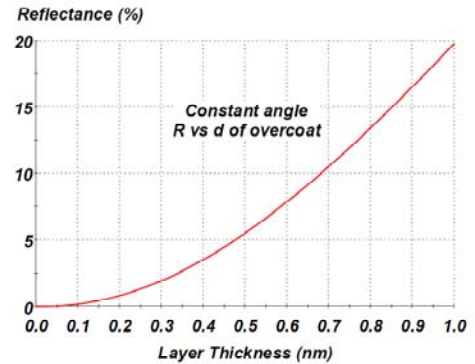
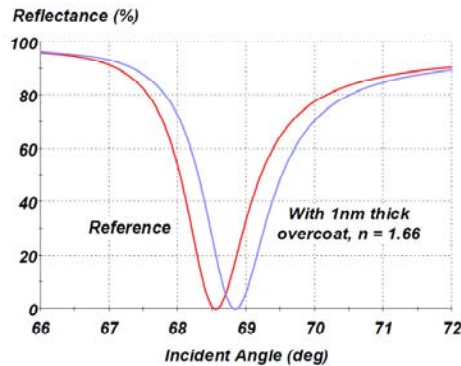
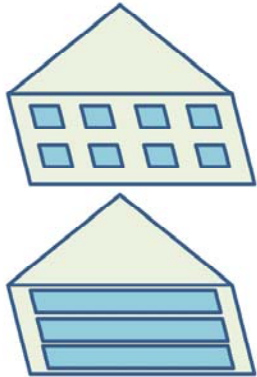
Total internal reflection for p-polarized light is frustrated by a thin layer of a metal like silver on the outer side of the surface. The result is a very narrow resonance-like feature in angle of incidence known as a surface plasmon resonance because it is coupled to a wave on the outer surface of the metal. This outer wave can easily be perturbed by a very thin addition layer of material so that it can act as a very sensitive detector. This has been used very successfully in following cellular biochemical processes in real time and there are current commercial applications.

The addition of 1nm of dielectric material of index 2.00 to the outer silver surface in this arrangement results in a perceptible perturbation of the resonance.

It has been known for several centuries that internal reflection in a dielectric material at sufficiently high angles of incidence is total. More recently it has been found that when metal layers are added to the totally reflecting surface, light that is polarized with the electric vector in the plane of incidence (p-polarization) behaves in a strange way. Provided the metal is of the correct thickness, which depends on the optical properties of the metal, the total p-reflectance can fall to zero in a quite narrow resonance-like feature. Silver and gold give very narrow reflectance dips and they are much used in this application. The dip is associated with a propagating electromagnetic wave that is pinned to the outer surface of the metal and is very sensitive to surface conditions. The wave is properly called a surface plasmon polariton but the resonance is usually known simply as a surface plasmon resonance. The sensitivity to surface conditions makes the resonance move in angle when even very small amounts of material are added to the surface and so it can be used as an extremely sensitive detector of material. There are many applications.

Multi-Channel Detectors

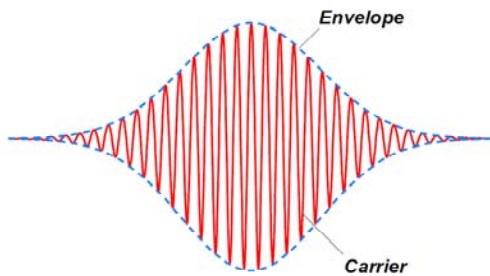
Suitable receptors can be fixed to the outer metal surface supporting a surface plasmon and the binding can be followed in real time as a record of changes in the resonance. Certain pathogens, small amounts of *Escherichia coli*, for example, have been successfully detected. An important advantage is the rapid response. Multiple channels can be arranged.



See: Homola, J., "Surface plasmon resonance sensors for detection of chemical and biological species," *Chemical Reviews* 108(2), 462-493 (2008).

The surface plasmon resonance can be used in biochemistry and in medicine to detect special proteins and pathogens through a process known as binding. The outer surface of the metal is treated with receptors to which the protein or pathogen to be detected will bind. The binding increases the thickness of the film on the metal surface and moves the resonance. Very small amounts of specific material can be detected in real time. The high angle of incidence in the example is because the outer medium is assumed to be water whereas in the previous example it was assumed to be air. Such techniques are already being commercially exploited.

A Short Pulse



The envelope moves at the *group velocity*

The carrier moves at the *phase velocity*

Except in a vacuum, these velocities are different because of dispersion.

The effects are linear and so we can treat the pulse as a continuous collection of spectral components of the form:

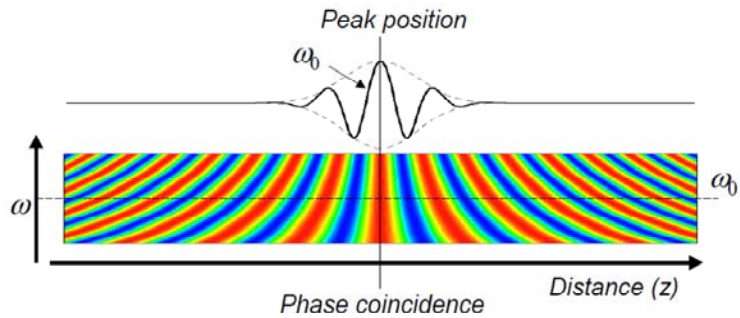
$$E = \mathcal{E} \exp[i(\omega t - \kappa z)] \quad \kappa = 2\pi n/\lambda$$

The velocity of this wave is $v = \omega/\kappa$

The sketch shows the electric field of a short pulse. The pulse consists of an envelope on top of a carrier. If we could actually see the pulse like this we would probably notice that the carrier is moving at a different velocity from that of the total pulse. They will move together only in a vacuum. The pulse velocity, which is that of the envelope, is known as the group velocity and that of the carrier as the phase velocity. These are old terms with a long history and we still use them. Because we are dealing with linear effects we can represent the pulse as a spectrum of harmonic components. Pulses that have a time length measured in femtoseconds (10^{-15} seconds = 1 femtosecond) are known as ultrafast and represent a growing field of research and application. Light in a vacuum travels at around 300 nanometres in 1 femtosecond. This means that when the pulse illuminates an optical coating of any complexity, the pulse reflected from the rear surface lags significantly behind that reflected from the front so that all kinds of interesting effects occur. Incidentally, although telecom optical pulses are measured in picoseconds, the coatings involved in telecom are so complex that similar effects occur there and have to be taken into account.

A Short Pulse

This illustrates the spectral components of the pulse. The colors indicate the phase. The shorter the pulse the wider the distribution. The peak of the pulse envelope corresponds to the coincidence of all the phases of all the spectral components.



We assume $z = 0$ and $t = 0$ as the origin and can write this condition as:

$$\omega_0 t - \kappa_0 z = \omega t - \kappa z = (\omega_0 + \Delta\omega)t - (\kappa_0 + \Delta\kappa)z$$

This reduces to: $\Delta\omega \cdot t = \Delta\kappa \cdot z$

Thus Group Velocity (the velocity of the envelope) is: $z/t = \Delta\omega/\Delta\kappa = d\omega/d\kappa$

The Phase Velocity (the velocity of the carrier) is: ω_0/κ_0

Fortunately we are still dealing with linear effects and so can represent the pulse by its spectrum. Here we represent the spectrum in terms of frequency and distance at a particular time. The phase is denoted by the colors and the peak of the pulse is situated where there is a coincidence in the value of phase across the whole spectrum. By altering the phases of the components without altering their amplitudes we can actually change the position of the pulse and even its shape. The important aspect of the change in phase is its variation as a function of the angular frequency, ω . A constant derivative of phase with respect to ω will tilt the lines of constant phase with the result that the time of arrival of the pulse will change. A second derivative implies that the top part of the distribution tilts the phase lines in the opposite direction from those below. The result is that the bottom part of the diagram shows a phase coincidence at a different position from the phase coincidence for the top part. At each of these phase coincidences the other part of the distribution has phases so jumbled that the fields cancel out. This means that the pulse starts at one position with one carrier and ends at another with a carrier of different frequency. The pulse is said to be broadened and chirped. An important application of optical coatings is to cancel out the broadening and chirping of a pulse that has been broadened and chirped by some other mechanism. The first three derivatives of phase with respect to ω are the most important ones.

The Effect of a Coating

A coating can keep the amplitudes constant but change the phases of the various spectral components. We recognize particularly three important attributes of phase.

$$-\frac{d\varphi}{d\omega} \quad \text{Group Delay (units of time)}$$

$$-\frac{d^2\varphi}{d\omega^2} \quad \text{Group Delay Dispersion (units of time}^2\text{)}$$

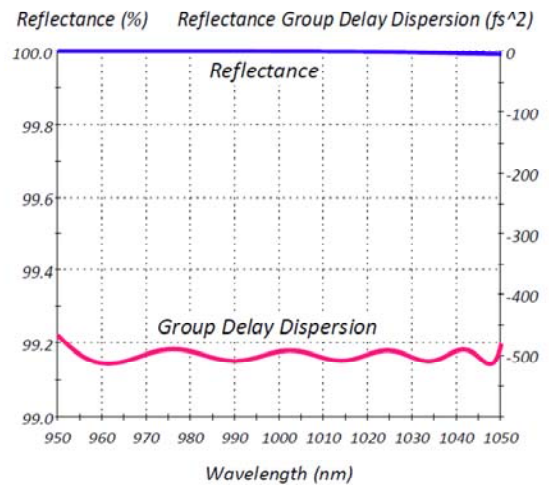
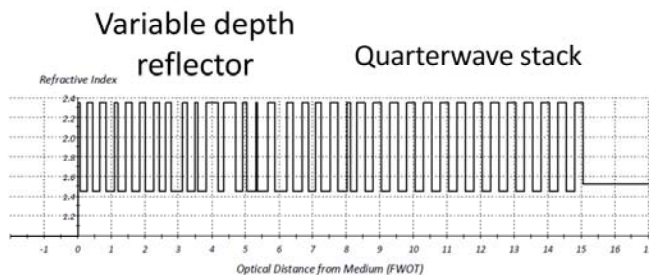
$$-\frac{d^3\varphi}{d\omega^3} \quad \text{Third Order Dispersion (units of time}^3\text{)}$$

Within limits, these quantities are susceptible to design. It is less difficult to do this in reflection.

Here the first three derivatives (note the minus signs) are shown with the names that are assigned to them. Phase is something we can manipulate in the design of the coating but it is important to note that we are unable to defeat nature. Although a negative group delay means that a pulse arrives sooner it is not possible to design a coating where the pulse will turn around in reflection before it reaches the mirror. The specification can readily be written but coating design techniques simply fail to yield a suitable result.

A dispersive reflector for ultrafast applications

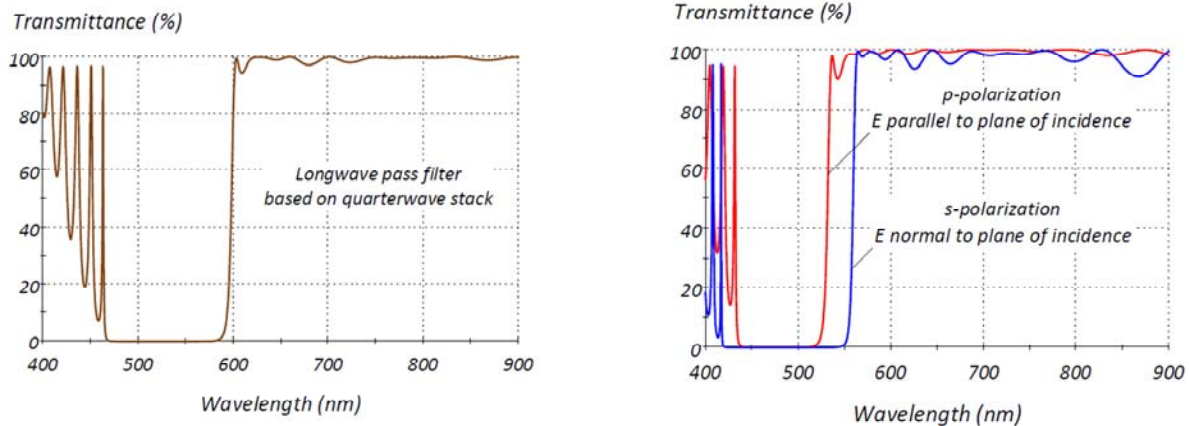
This 67-layer reflector is designed to present a uniformly high reflectance with a group delay dispersion of -500 fs^2 . It consists of a base quarterwave stack reflector with a phase correction section in front that takes the form of a variable depth reflector.



This is an example of a coating designed to present a group delay dispersion of -500 fs^2 over a given spectral range. Depending on frequency, the light reaches a certain depth in the coating and that effect, as well as the behavior of certain resonators, delays its reemergence so that the phase at that particular frequency is altered accordingly compared with all the other frequencies. Mostly the coatings are designed by automatic computer methods because analytical approaches are very involved and difficult. Production requires exception layer accuracy and there can be serious variations in the characteristic as a result. A trick that is frequently used is to have multiple reflections at a series of coatings chosen so that errors in one characteristic are cancelled by opposite errors in another. This involves a mixing and matching operation and relies on the linear nature of the processes.

Sensitivity to Tilting

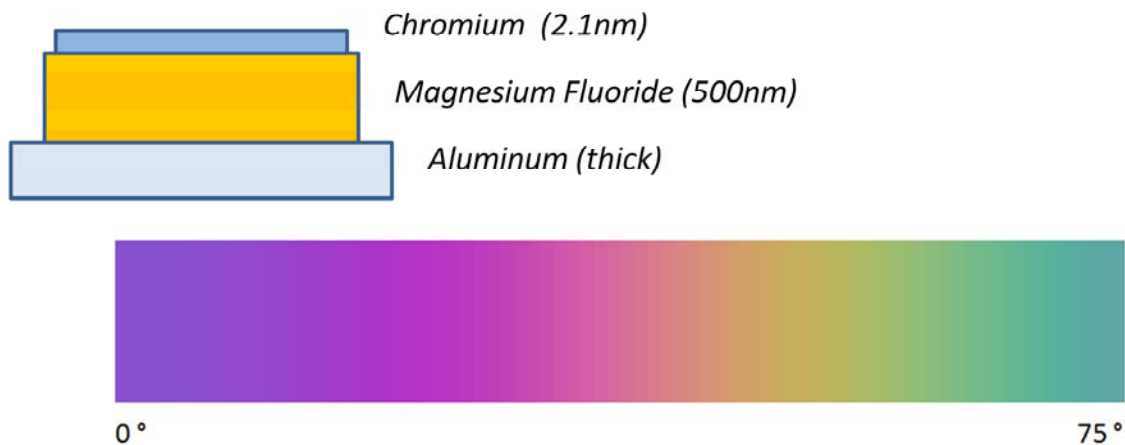
Interference largely determines the properties of optical coatings. Because path differences shrink at oblique incidence, the characteristics of coatings shift to shorter wavelengths. There are also some effects of polarization. Sometimes the characteristic can be distorted.



Interference effects depend on path differences and path differences depend on propagation angle. Thus we find that the characteristics of optical coatings vary with angle of incidence. The two most important and common effects that increase with angle of incidence (roughly a cosine effect) are first a shift of the characteristic to shorter wavelengths and second a splitting of the characteristic where the p-characteristic becomes weaker and the s-characteristic becomes stronger. P-polarization is the linear mode where the electric vector is in the plane of incidence that contains the ray direction and the surface normal. S-polarization is the linear mode with the electric vector normal to the plane of incidence and, therefore, parallel to the surface. The s comes from the German *senkrecht* meaning perpendicular. Sometimes there is a third effect, distortion of the characteristic. This third effect depends very much on the design details.

Iridescence – the Colors change with Angle of Incidence

Path differences become shorter with increasing angle of incidence and so interference colors have an additional dimension in that they change as the view becomes more oblique. A simple decorative coating with the structure shown exhibits this change and is much used in decorative applications.



Optical coatings can be very colorful and we can use the tilting effect to add a dimension to the color not available in dyes. Here we have a coating deliberately designed to present a large color shift with incidence. It is used in many decorative applications and also as a double-sided coating ground into fragments to form a color-variable pigment that can be used in inks and paints. A major application of a color-variable ink is in forgery prevention. Many countries, including the United States, use features printed in color variable ink on currency notes to defeat forgery by photocopying.

Interference Colors in Reflection

The substrate for this interference painting by David Cushing is aluminum coated with Inconel®. This substrate was then treated with a tantala and silica narrowband reflection filter.

See D. Cushing, "Rainbow filters," *SVC News Bulletin (Spring)*, 32-33 2009 for a description of the coating design.



This is a photograph of a painting by David Cushing produced by varying thicknesses and local angle of incidence of an optical coating. The substrate is aluminum foil. Another example by David Cushing hangs on one of the floors of the West Wing of the Meinel Building of Optical Sciences.

Colors of an Oil Film on Water

Thin film color analysis techniques can be used to reproduce the colors exhibited by an oil film on water. The central strip is a calculation of the colors of an oil film on water of linearly wedged thickness from 0nm (top) to 500nm (bottom) and illuminated by daylight.

This composite illustration uses a photograph from Wikimedia Commons (Diesel spill on a road. By Guinnog) and so is freely available under the terms of the Wikimedia Commons license.



This is simply a bit of fun where a calculated color strip showing the colors of oil on water is superimposed over an actual photo of the colors of an oil slick on a puddle on a road. The agreement is close.

Conclusion

It is rare to find in an optical system a surface that does not carry an optical coating. As long as there is optics there will be optical coatings.

Optical coating is often described as an enabling technology because it enables the performance of an optical system. I hope this short description that has touched only a part of the subject has demonstrated that an optical coating can also be the central core of an optical system that not just enables performance but actually defines it.

There is much more to optical coatings than can be covered in an hour or so. Thin-film optics is one of the oldest divisions of optics but also one of the newest because optical coatings are a necessary feature of virtually every branch of optics technology. Wherever there is optics there will be an optical coating.