ITALIAN NATIONAL AGENCY
FOR NEW TECHNOLOGIES, ENERGY AND
SUSTAINABLE ECONOMIC DEVELOPMENT

Optical Filters for Space Instrumentation

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Optical Filters

- Optical Filters are commonly used in Space instruments
- They are in some cases the most critical elements for the successful instrument operation
- The optical components must survive in the environmental conditions of Space and maintain their performance

Outline

1)

- What Optical Filters are?
- Which are the most widely used filters?
- How to design and fabricate them?

……………………………………………………………………….

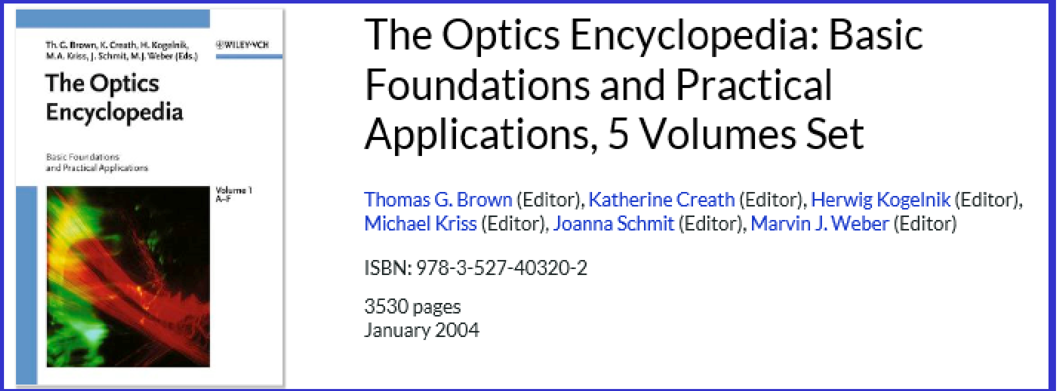
2)

- Applications for Space: two examples
  - Imaging spectrometer (for Earth Observation)
  - Lightning imager (Meteosat)

Definitions

- **What is an Optical Filter?**

  from the Optics Encyclopedia
  (Wiley & Sons)

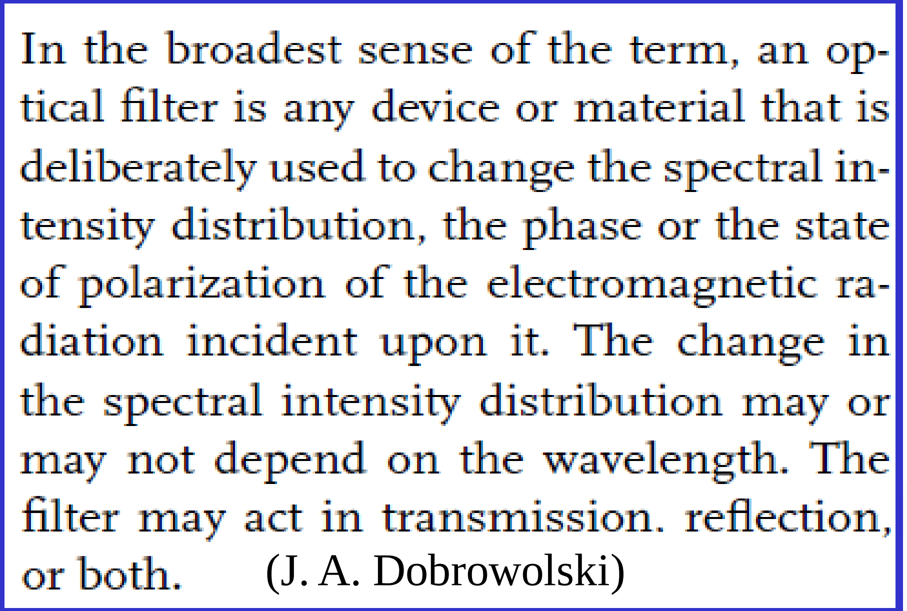


The Optics Encyclopedia: Basic Foundations and Practical Applications, 5 Volumes Set

Thomas G. Brown (Editor), Katherine Creath (Editor), Herwig Kogelnik (Editor), Michael Kriss (Editor), Joanna Schmit (Editor), Marvin J. Weber (Editor)

ISBN: 978-3-527-40320-2

3530 pages
January 2004

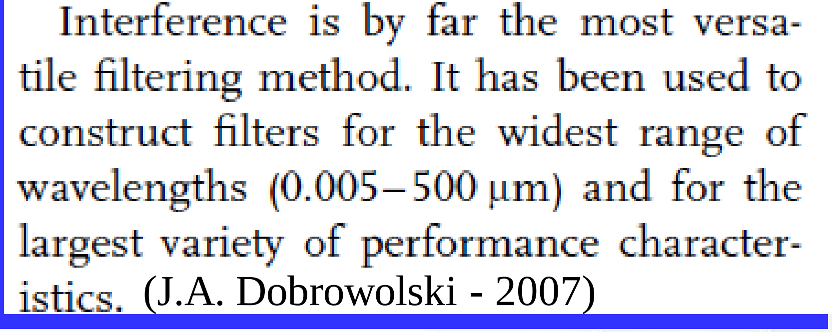


In the broadest sense of the term, an optical filter is any device or material that is deliberately used to change the spectral intensity distribution, the phase or the state of polarization of the electromagnetic radiation incident upon it. The change in the spectral intensity distribution may or may not depend on the wavelength. The filter may act in transmission, reflection, or both. (J. A. Dobrowolski)

http://onlinelibrary.wiley.com/book/10.1002/9783527600441

Optical filters: basic concepts

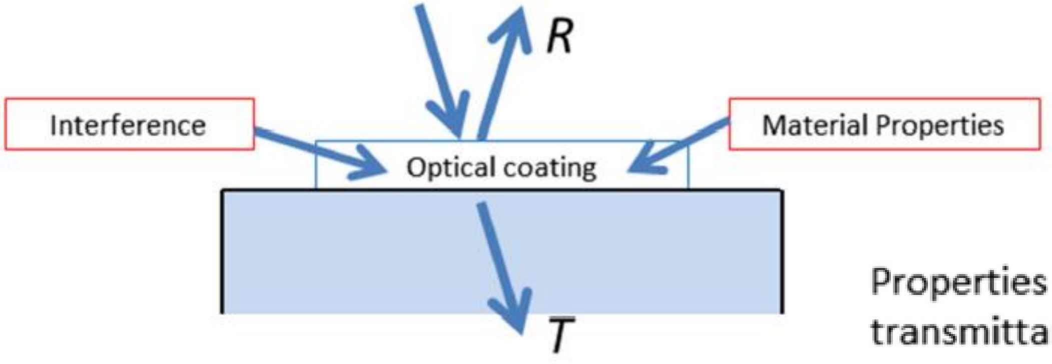
- Types of optical filters
  - Antireflection coatings, mirrors, bandpass filters, short-wave and long-wave pass filters, rejection filters, dichroic filters, beam splitters, gain flattening filters, etc.
- Physical phenomena on which filters are based
  - Absorption, reflection, holography, diffraction, scattering, interference in thin films, etc.
- Interference in thin films
  - The most versatile method



Interference is by far the most versatile filtering method. It has been used to construct filters for the widest range of wavelengths (0.005–500 µm) and for the largest variety of performance characteristics. (J.A. Dobrowolski - 2007)

Optical interference coatings

- Optical interference effects in thin layers, together with the optical properties of materials, determine the performance of optical coatings



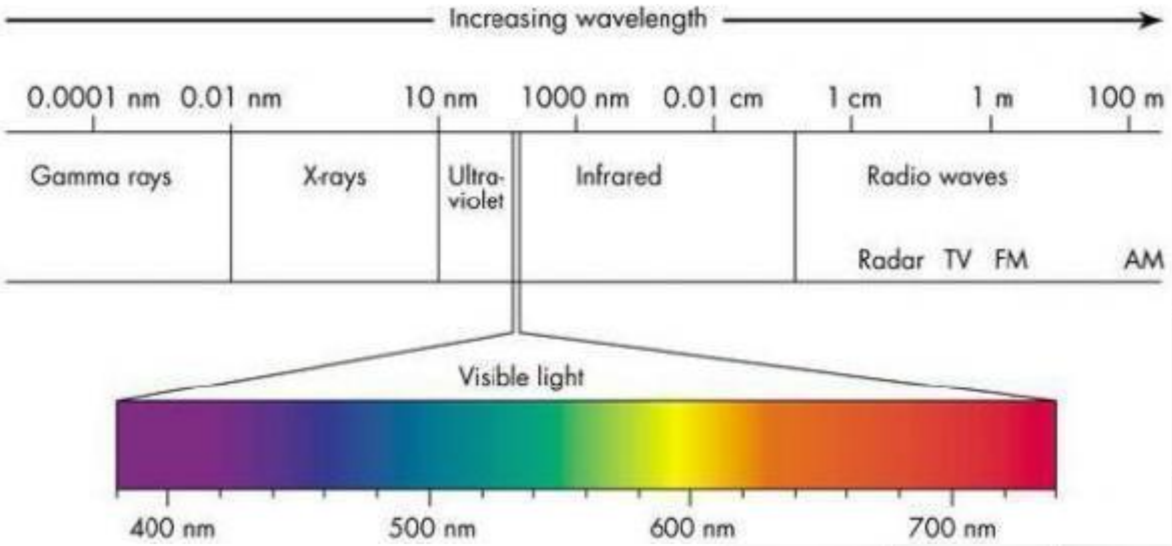
H.A. Macleod: Optical Coatings

Properties of **particular** interest are the reflectance, *R* and the transmittance *T*. They measure the fraction of the incident power density that is either respectively reflected or transmitted.

- **Wavelength range**

Currently the spectral region for which optical filters are constructed extends from about 5 nm to 500 µm.

However, the ultraviolet - visible - near infrared spectrum is the most common operating range and many applications are concentrated at such wavelengths.



Optical Coatings: materials

Complex refrative index **(n-ik)**

n refractive index, **k** extinction coefficient ($\alpha=4\pi k/\lambda$ absorption coefficient)

The refractive index changes with λ: **dispersion**

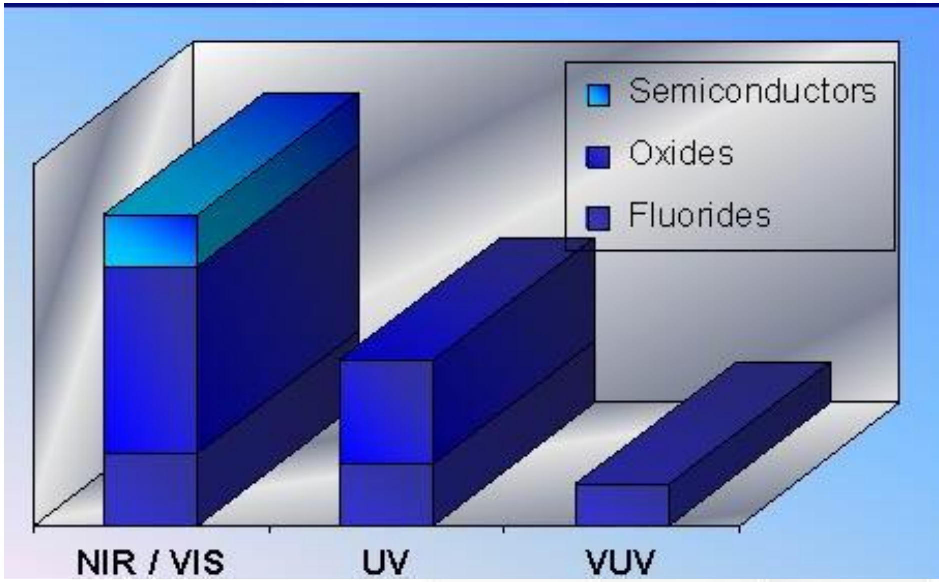
High refractive index materials: TiO_2, Ta_2O_5, $Y2O_3$, HfO_2, LaF_3, ZnSe, Si...
(semiconductors with large dispersion: AlAs, GaAs, AlGaAs, InGaAs..)
Low refractive index materials: SiO_2, MgF_2,...

Short wavelength materials (ultraviolet):

limited choice because of high absorption below the cut wavelength

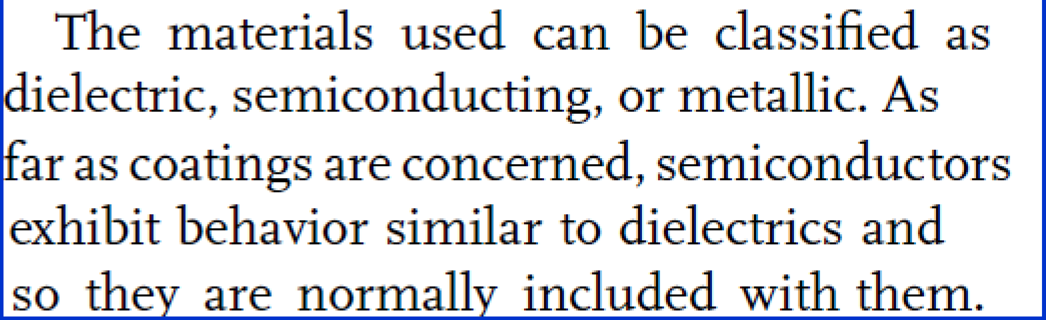
Long wavelength materials (infrared):

presence of absorption bands

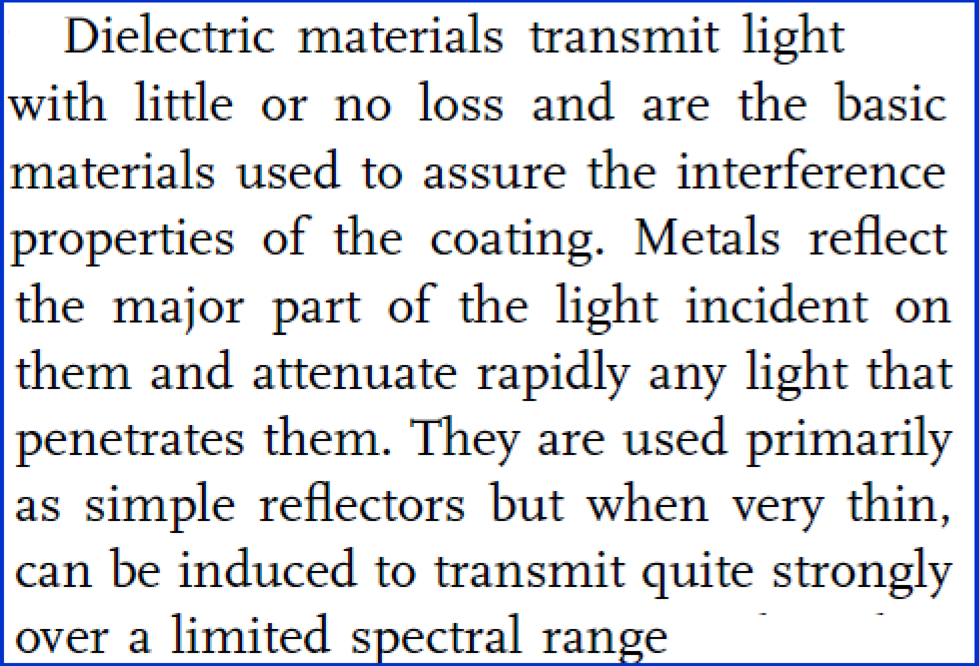


Optical coatings: materials

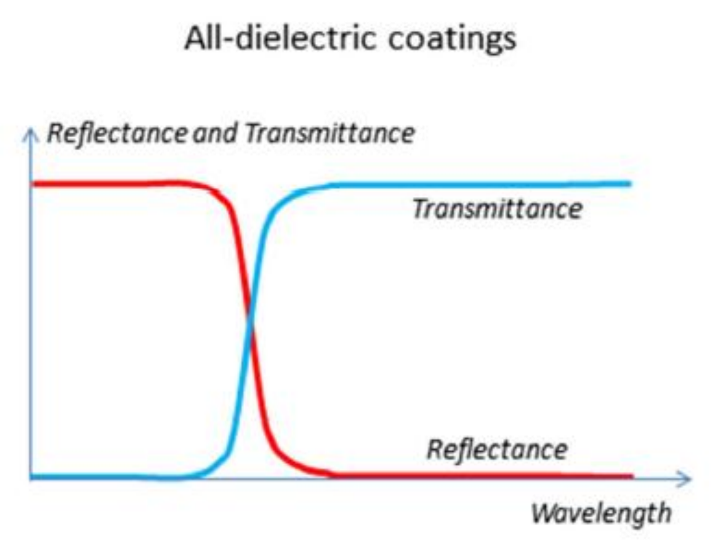
- Dieletric materials and metals



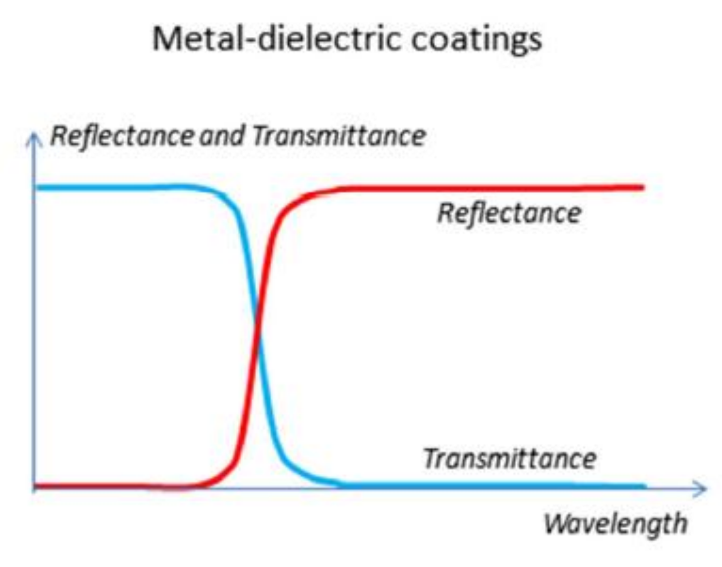
The materials used can be classified as dielectric, semiconducting, or metallic. As far as coatings are concerned, semiconductors exhibit behavior similar to dielectrics and so they are normally included with them.



Dielectric materials transmit light with little or no loss and are the basic materials used to assure the interference properties of the coating. Metals reflect the major part of the light incident on them and attenuate rapidly any light that penetrates them. They are used primarily as simple reflectors but when very thin, can be induced to transmit quite strongly over a limited spectral range



All-dielectric coatings

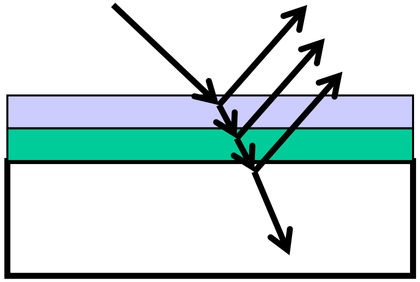


Metal-dielectric coatings

H.Angus Macleod: Optical Coatings in **Optics Encyclopedia**

Interference in thin films

- Thin-film optical filters
  - *Physical principle*: interference of the electromagnetic radiation
  - *Materials*: characterized by their complex refractive index (n - ik)
  - *Layers*: characterized by the geometrical thickness d (comparable to the wavelength) and the phase thickness δ = 2π (n-ik) d/λ



air

thin films (from 1 to some hundred)

substrate (e.g.: glass)

- **Calculation of coating spectral performance**
  - Based on Maxwell equations
  - The electric B and magnetic C fields are calculated through a transfer matrix (η_j = refractive index of layer j)

$$\begin{bmatrix} B \\ C \end{bmatrix} = \left\{ \prod_{j=1}^{q} \begin{bmatrix} \cos\delta_j & \dfrac{i\sin\delta_j}{\eta_j} \\ i\eta_j \sin\delta_j & \cos\delta_j \end{bmatrix} \right\} \times \begin{bmatrix} 1 \\ \eta_{\mathrm{sub}} \end{bmatrix}$$

Reflectance

$$R = \frac{(\eta_0 B - C)(\eta_0 B - C)^*}{(\eta_0 B + C)(\eta_0 B + C)^*}$$

Transmittance

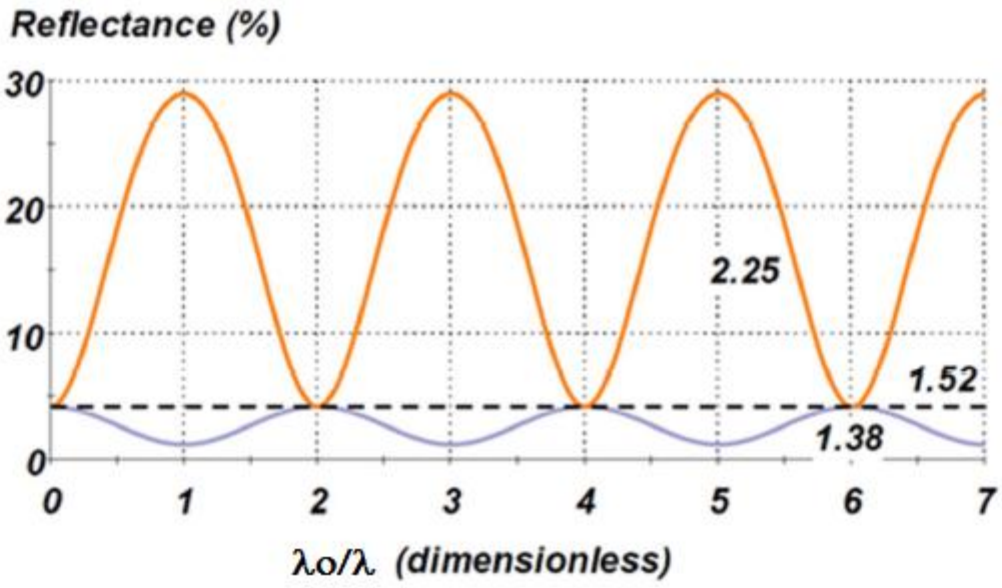
$$T = \frac{4\eta_0\,\mathrm{Real}(\eta_{\mathrm{sub}})}{(\eta_0 B + C)(\eta_0 B + C)^*}$$

Optical Coating Design

H.Angus Macleod: Thin-Film Optical Filters 4th ed. (CRC Press, New York 2010)

The detailed theory is not necessary to understand the functioning of coatings. It is useful to accept a few simple design principles

1. Quarter-wave layers give maximum interference effect.
2. Half-wave layers give zero interference effect. They are known as *absentee* layers.
3. Dielectric layers become weaker in their effect as the wavelength increases.
4. Metallic layers become stronger in their effect as wavelength increases.



- **Quarter-wave layers: nd = λ_0 /4**
- **Half-wave layers: nd = λ_0 /2**

Reflectance of a single layer of index 2.25 or 1.38, on a glass substrate of index 1.52

$R_{\text{substrate}} = [(1- n_{\text{sub}})/(1+n_{\text{sub}})]^2$

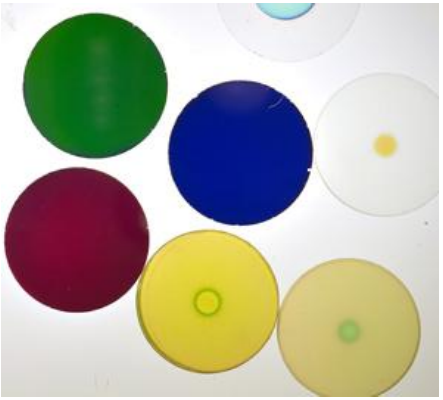
The low index layer is a potential antireflection coating
The high index layer could be used as a beamsplitter

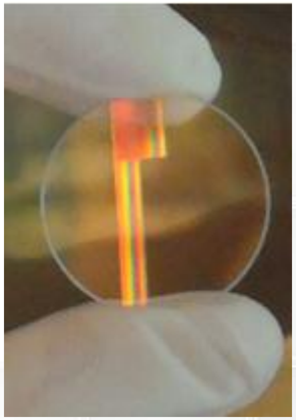
$R_{\lambda o} = [(1- n_{\text{film}}^2/n_{\text{sub}})/(1+n_{\text{film}}^2/n_{\text{sub}})]^2$

Optical Coatings: basic structures

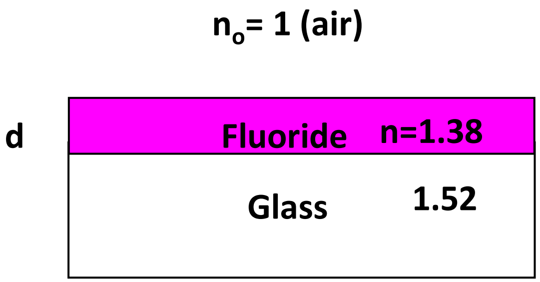
Classical filters commonly used in space applications

- Antireflection coatings
  - Single wavelength
  - Wideband
- High reflection coatings
  - Narrow wavelength range
  - Large spectrum
- Filters
  - Edge filters
  - Broad-band-pass / narrow-band filters





Antireflection coatings



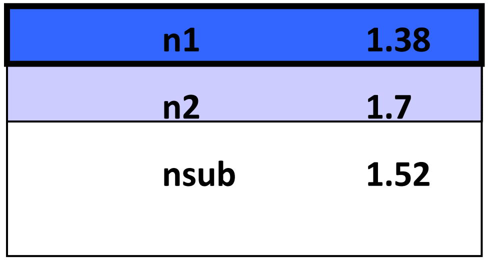
n_o= 1 (air)

d

Fluoride n=1.38

Glass 1.52

To achieve lower reflectance, if the substrate has a low index, it is useful to increase its reflectance with a first layer and then antireflect with a second layer



n1 1.38

n2 1.7

nsub 1.52

On a substrate of high index, like Ge (n=4), two quarter wave layers of materials with decreasing index are sufficient to antireflect it

Antireflection coating at a single wavelength:

- 1 quarter wave layer

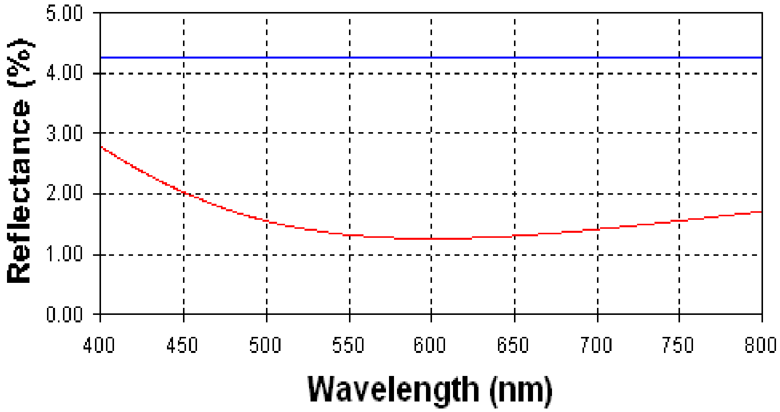
(nd=λ/4 ⇒ $\delta = 2\pi\, nd/\lambda = \pi/2$)

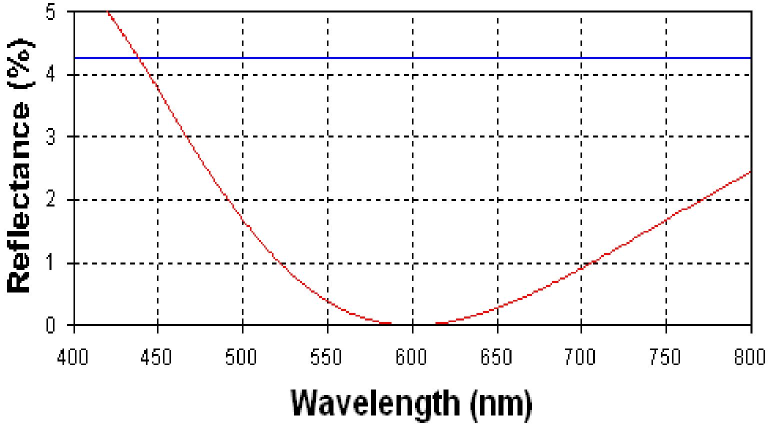
R=0 if $n_{film} = \sqrt{n_{sub}}$

- 2 quarter wave layers

R=0 if $n2/n1 = \sqrt{n_{sub}}$

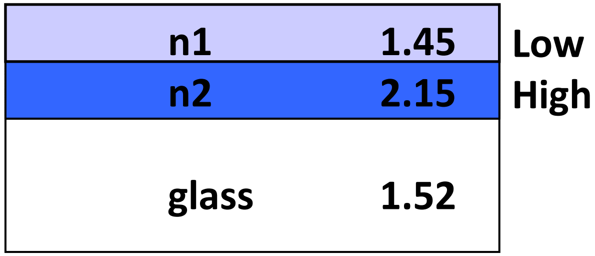
Otherwise non quarter wave layers must be used



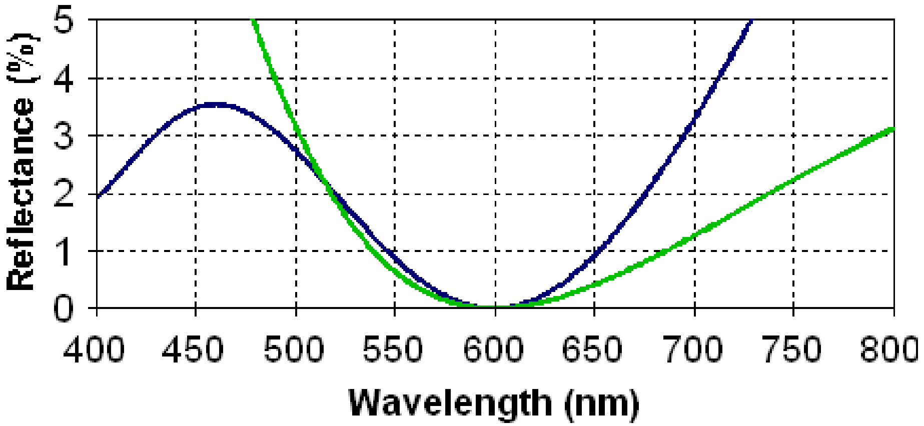


Antireflection coatings on glass

Non quarter wave AR coatings

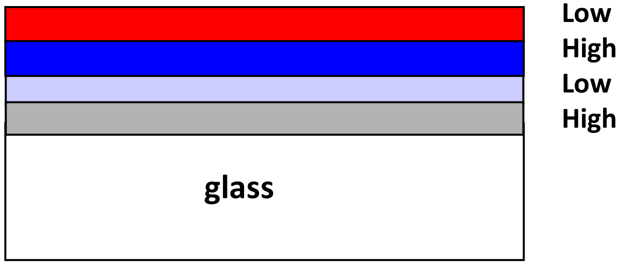


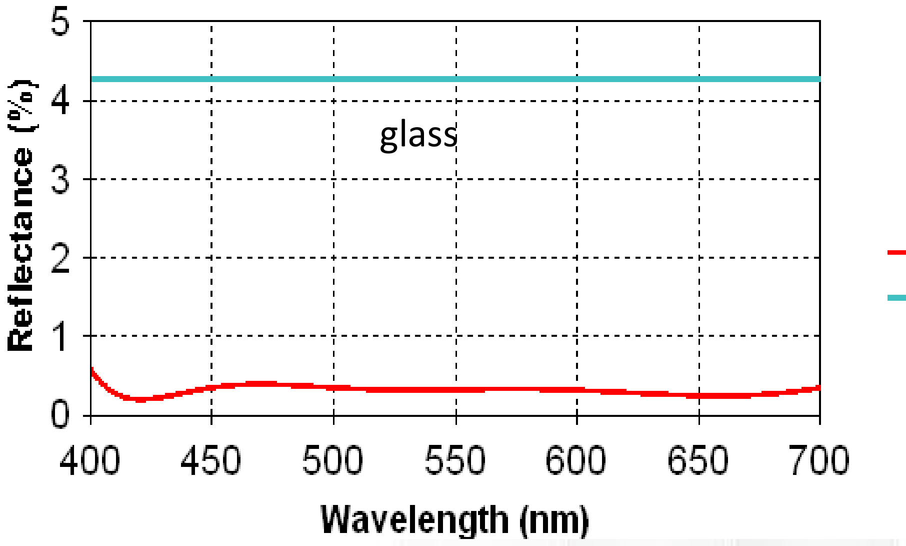
2 **non** quarter wave layers (V-coat)



blu: 1.67 high 0.71 low, **green:** 0.33 high 1.29 low

Wideband: 4 **non** quarter wave layers

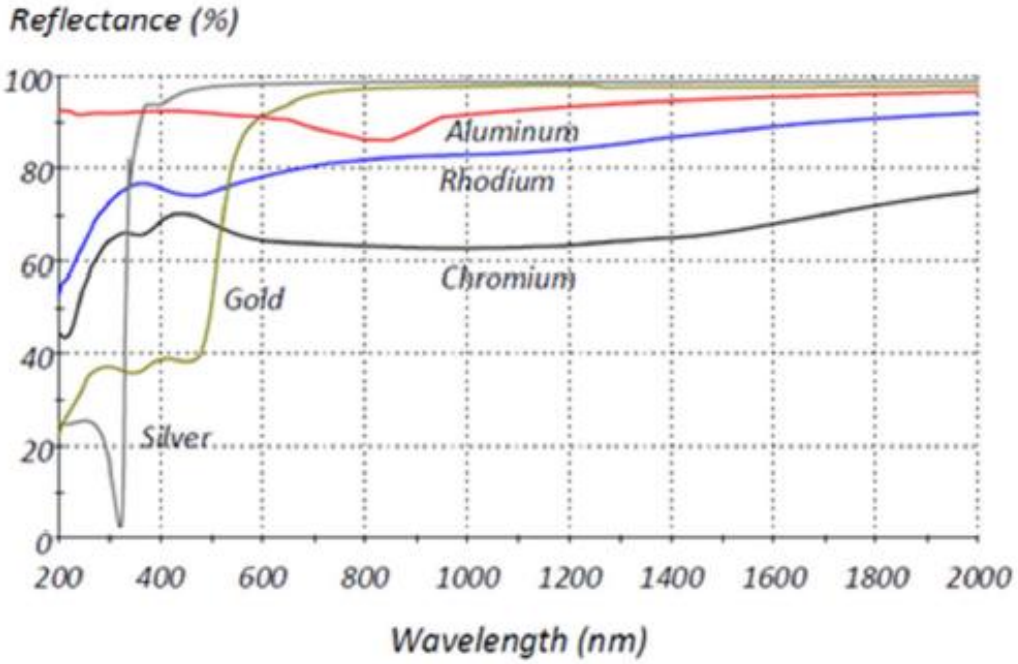


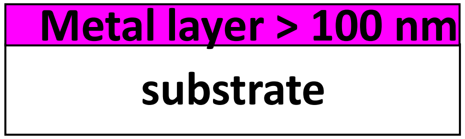


green: substrate, red: AR coating

Metal Mirrors

Metal Layers as Front Surface Mirrors





Metal layer > 100 nm

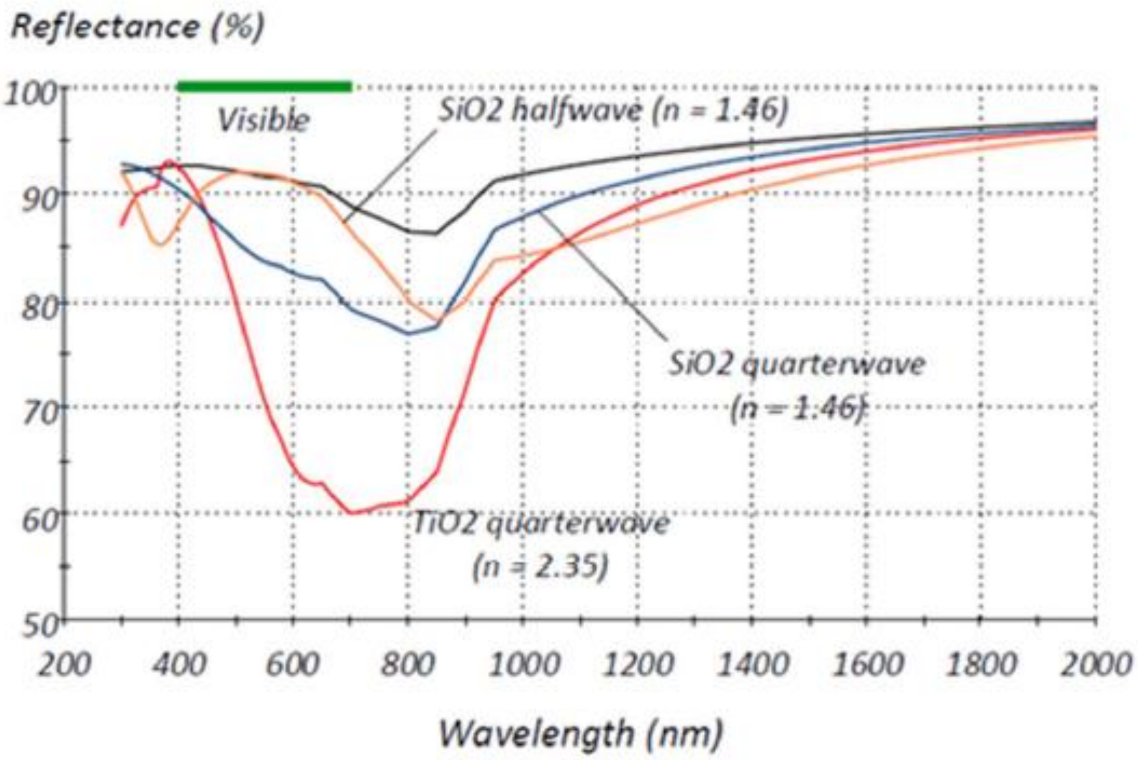
substrate

Silver has highest reflectance in the visible and infrared regions but is environmentally weak. Rhodium is rugged and stable and has low scatter losses. Rhodium and chromium are the usual materials of choice in aggressive environments. Aluminum has a high reflectance in the ultraviolet spectrum.

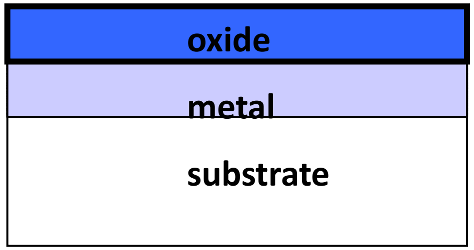
H.A. Macleod: Optical Coating Design

Coated metal mirrors

Protection of Front Surface Mirrors



A dielectric layer over a metal will reduce reflectance until the dielectric is close to a halfwave. The greater the index of the dielectric the greater the drop in reflectance.



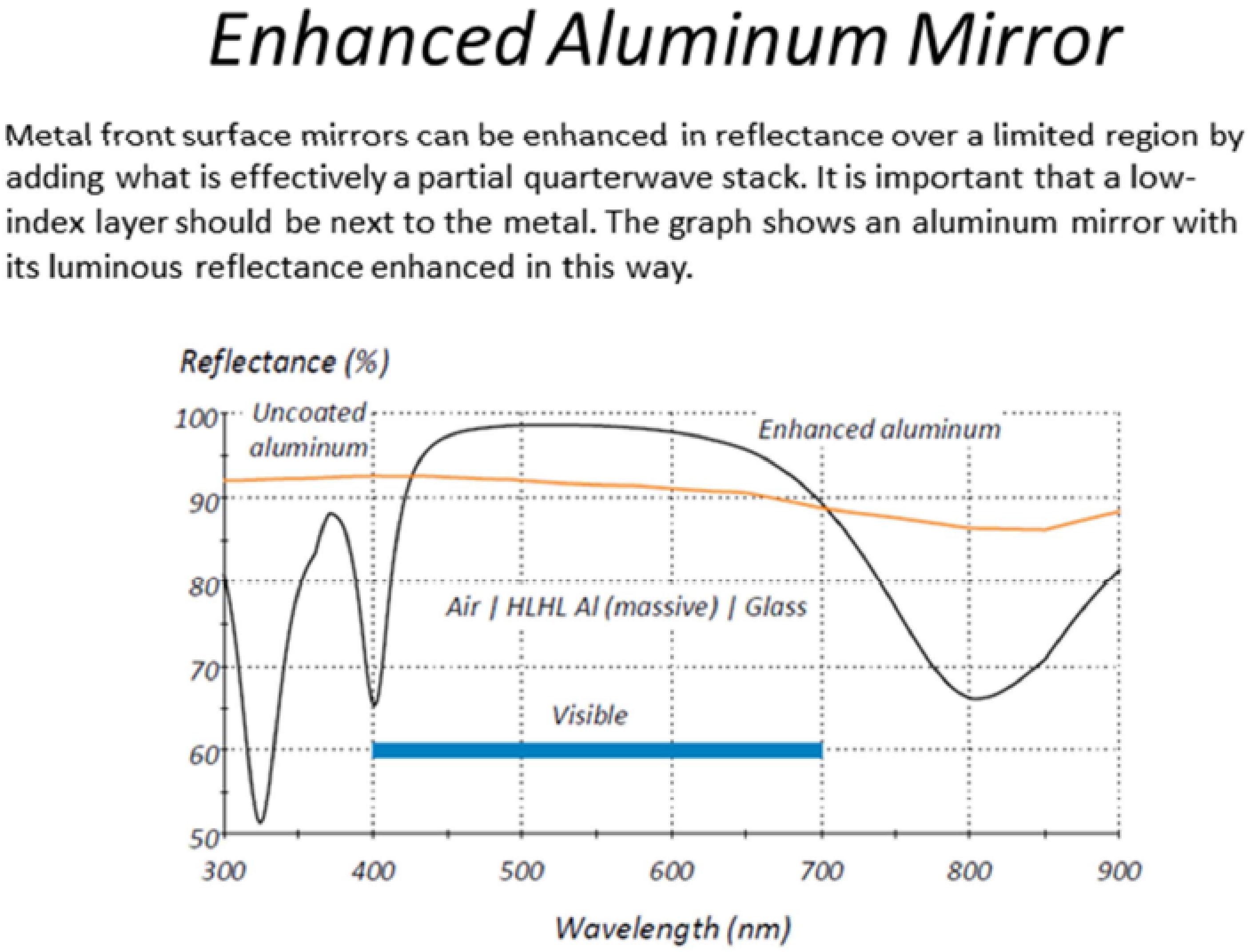
oxide

metal

substrate

H.A. Macleod: Optical Coating Design

Coated metal mirrors



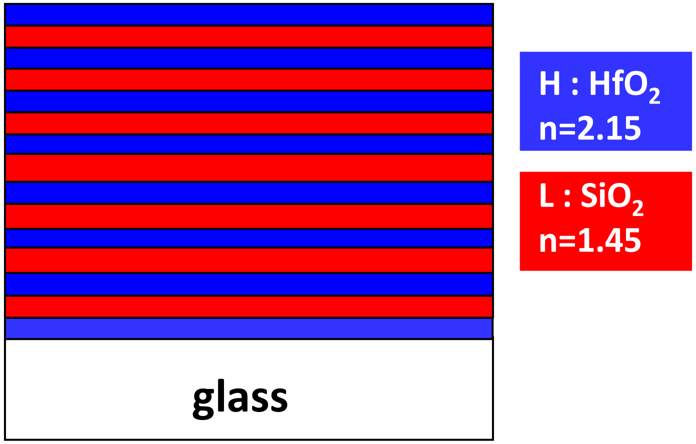
Enhanced Aluminum Mirror

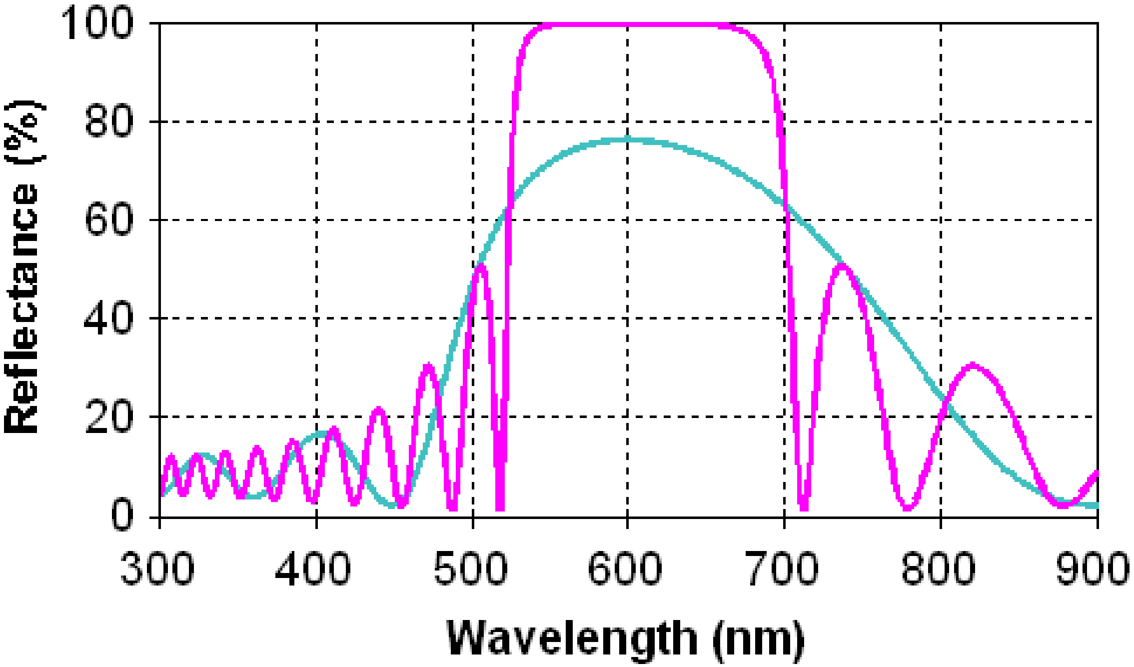
Metal front surface mirrors can be enhanced in reflectance over a limited region by adding what is effectively a partial quarterwave stack. It is important that a low-index layer should be next to the metal. The graph shows an aluminum mirror with its luminous reflectance enhanced in this way.

H.A. Macleod: Optical Coating Design

All-dielectric mirrors

Quarter-wave high reflection coatings: the coated substrate can be represented at λ_0 by a single refractive index N_{eff}





$$R = [(1-N_{eff})/(1+N_{eff})]^2$$

number of layers (external *H*)

$$N_{eff} = \left(\frac{n_H \ldots\ldots n_H}{n_L \ldots\ldots n_L}\right)^2 \times n_{sub}$$

even

$$N_{eff} = \left(\frac{n_H \ldots. n_H}{n_L \ldots\ldots}\right)^2 \frac{1}{n_{sub}}$$

odd

Dielectric mirror (quarter-wave) : 5 or 19 layers

Glass/ HLHLHLHLHLHLHLHLHLH /Air

$n_{(H,L)}\, d_{(H,L)} = \lambda_0 /4 \quad \lambda_0 = 600nm$

(odd number of layers with external *H*)

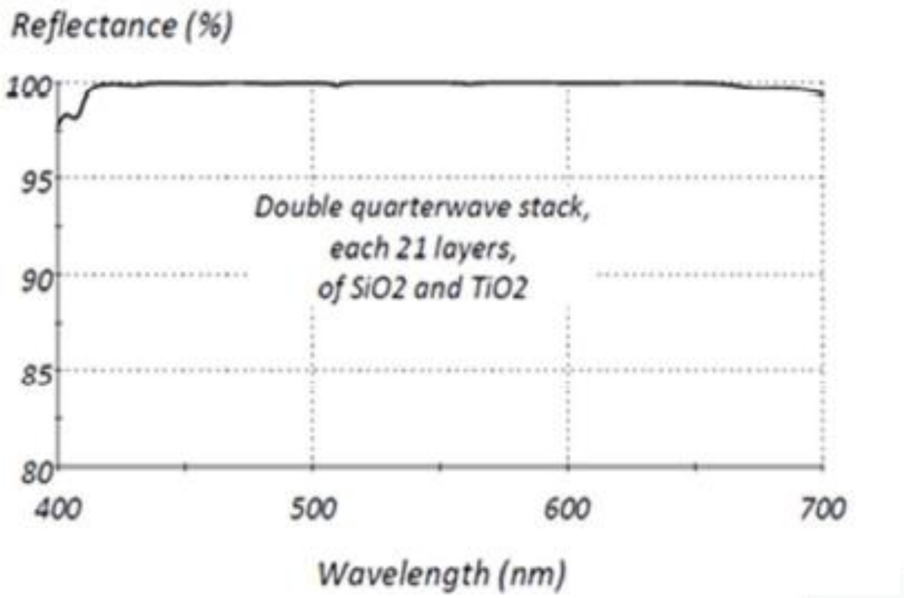
The maximum reflectance increases with the number of layers and with the index contrast

Broadband mirrors

- The reflectance of a single quarter-wave stack cannot cover a wide spectrum because the index contrast is insufficient

- A simple way of achieving high reflectance over a wide spectrum is to add one stack over another, centered at different reference wavelengths: λ_0 and λ_0' (a decoupling layer in between is necessary)

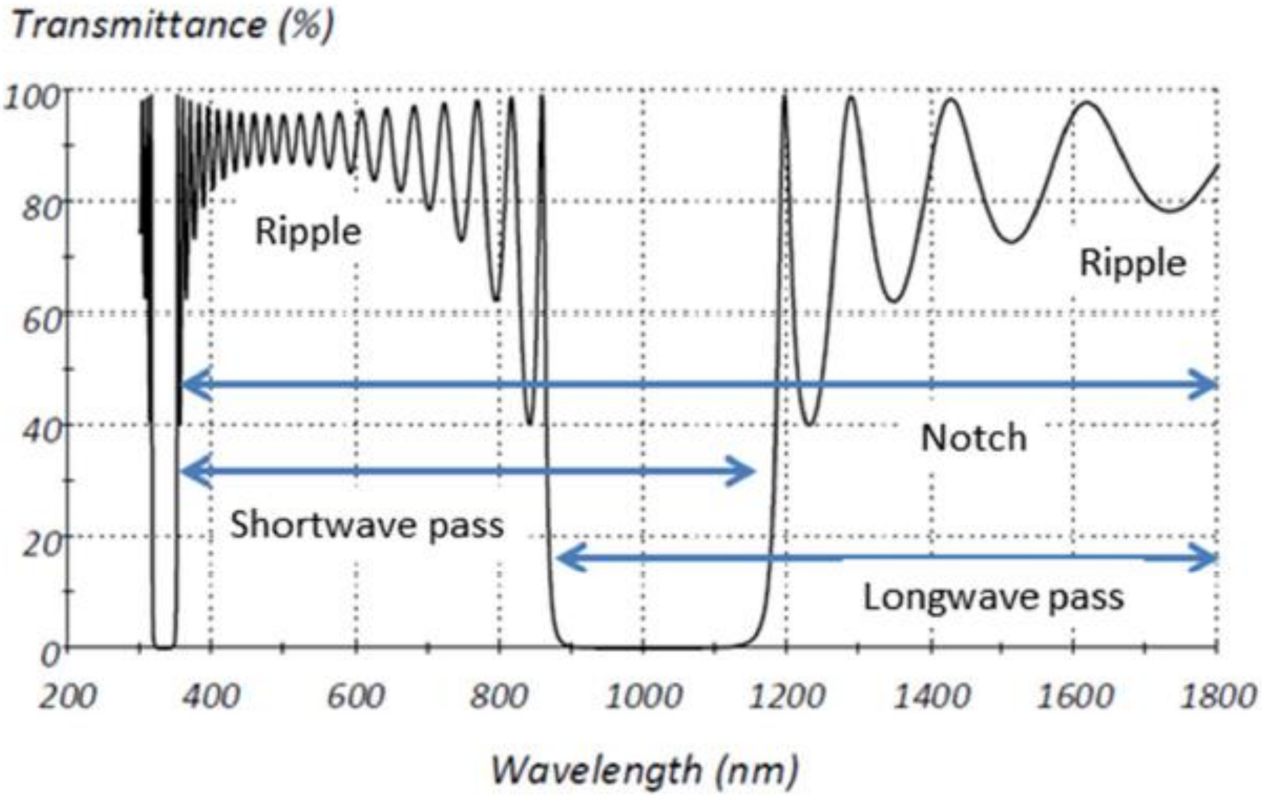
Glass/HLHLHLHL…….H L H'L'H'L'H'L'H'L'……….H'/Air



- An alternative way is the progressive increase of layer thicknesses, according to a specific rule

Different types of filters

Quarterwave Stack as a Filter



The quarterwave stack is an important building block for many kinds of filters. In addition to the above we have dichroic beam splitters and bandpass filters and still more applications when tilted. Ripple is the major defect

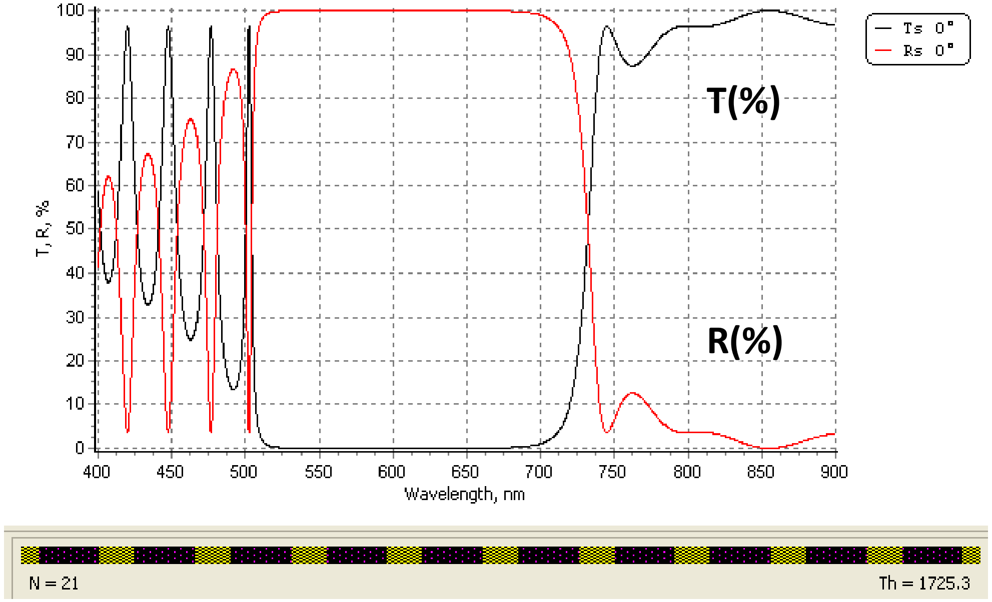
Ripple removal is a matching problem rather like designing an antireflection coating

H.Angus Macleod: Optical Coatings in **Optics Encyclopedia**

Edge filters

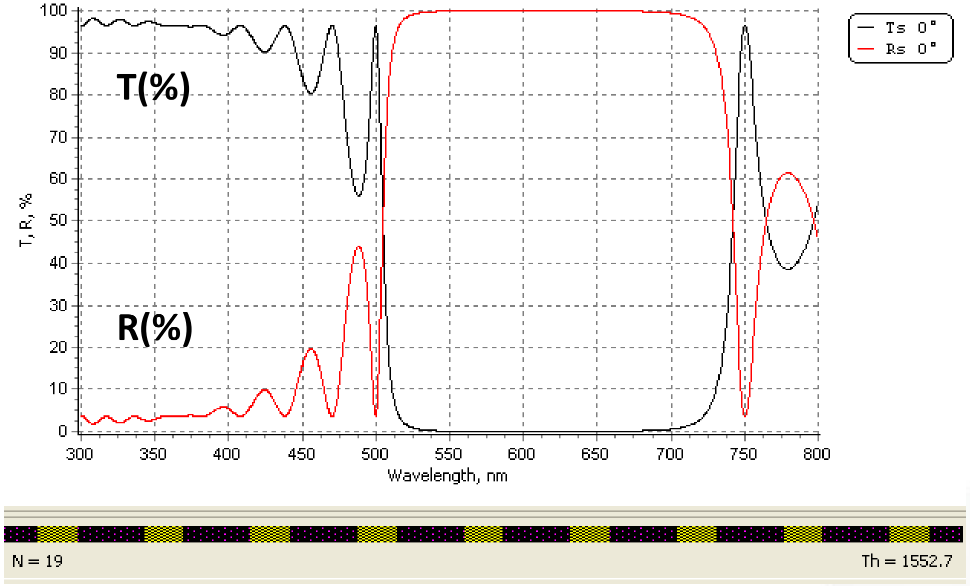
Long-wave and short-wave pass filters

nL: 1.38, **nH**: 2.35, λ_0= 600 nm



Glass/H/2 LHLHLHLHLHLHLHLHLHL H/2/Air

Long-wave pass filter (21 layers; external H/2)



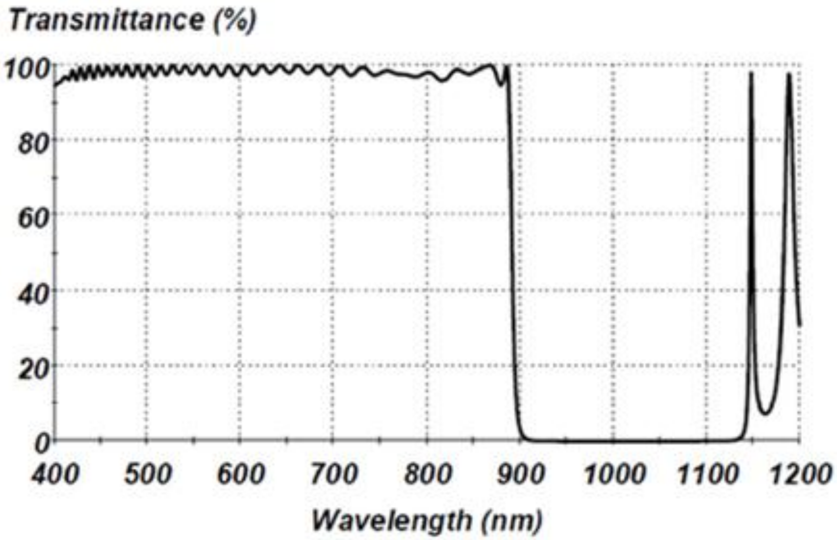
Glass/L/2 HLHLHLHLHLHLHLHLHL/2/Air

Short-wave pass filter (19 layers; external L/2)

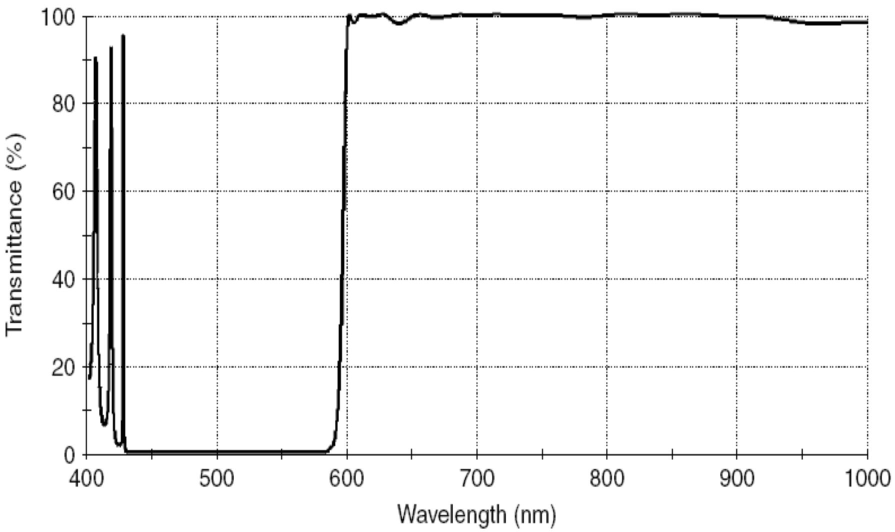
Ripple should be reduced

Short-wave and long-wave pass filters

This shortwave pass edge filter has been designed by starting with a suitable quarterwave stack and adopting some of the outermost layers as matching structures that are then adjusted in a refinement process by a machine. If the ripple is still not satisfactory then the process continues with still more layers assigned to the matching structures.



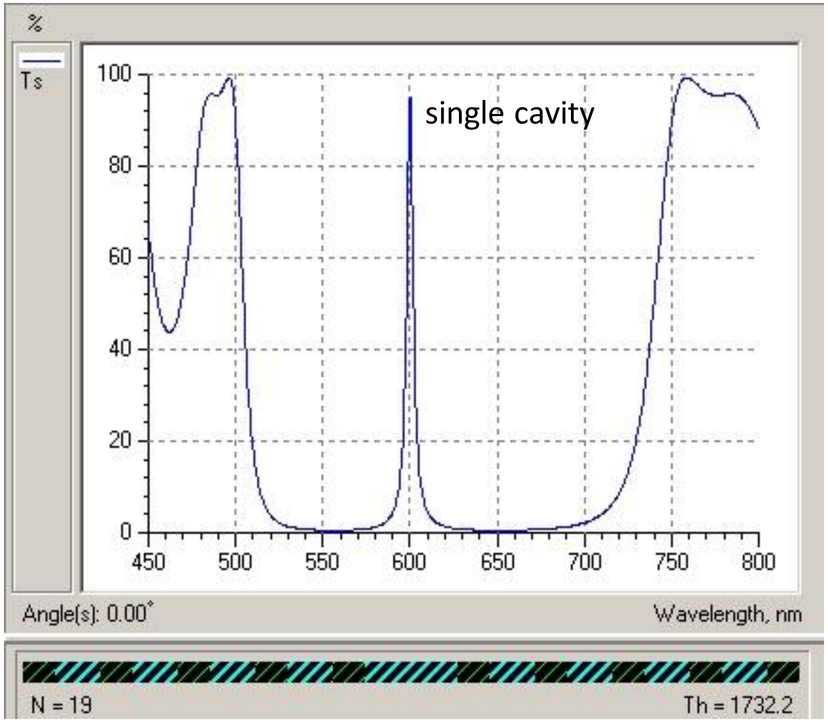
An example of a long-wave-pass filter based on a quarter-wave stack is shown (41 layers).Additional matching layers to reduce the ripple are included outside the basic quarter-wave structure. Sometimes, such components are used to separate light into two, or perhaps more, wavelength regions when the term dichroic beam splitter is used.



H.Angus Macleod: Optical Coatings in **Optics Encyclopedia**

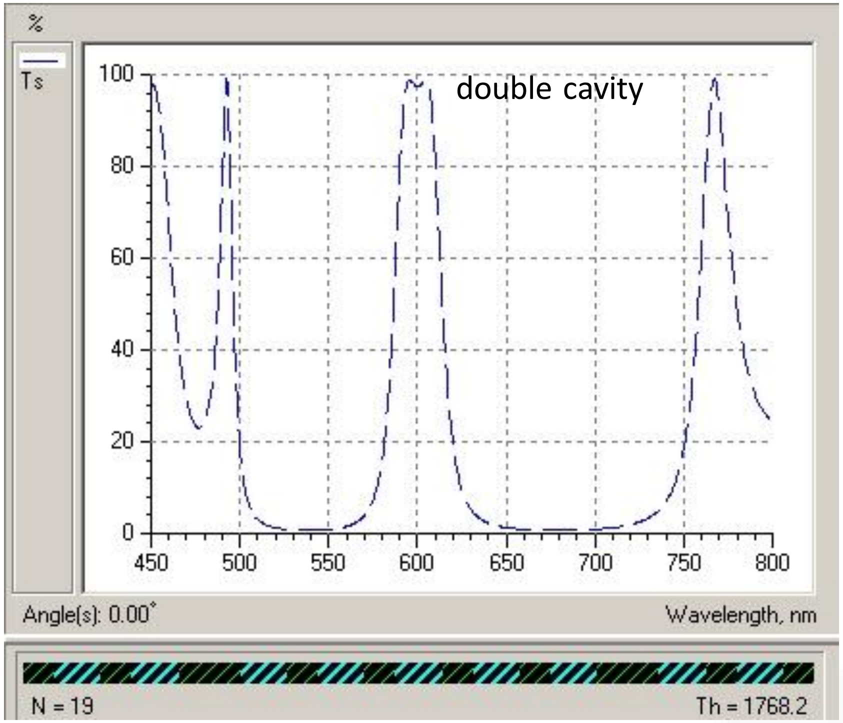
Narrow-band transmission filters

Two similar quarterwave stacks in series form a simple cavity structure sometimes known by the name Fabry-Perot because of the similarity to the well-known etalon. The cavity is the central set of halfwaves.



T(%)

Narrow-band transmission filters



single cavity: central half-wave layer

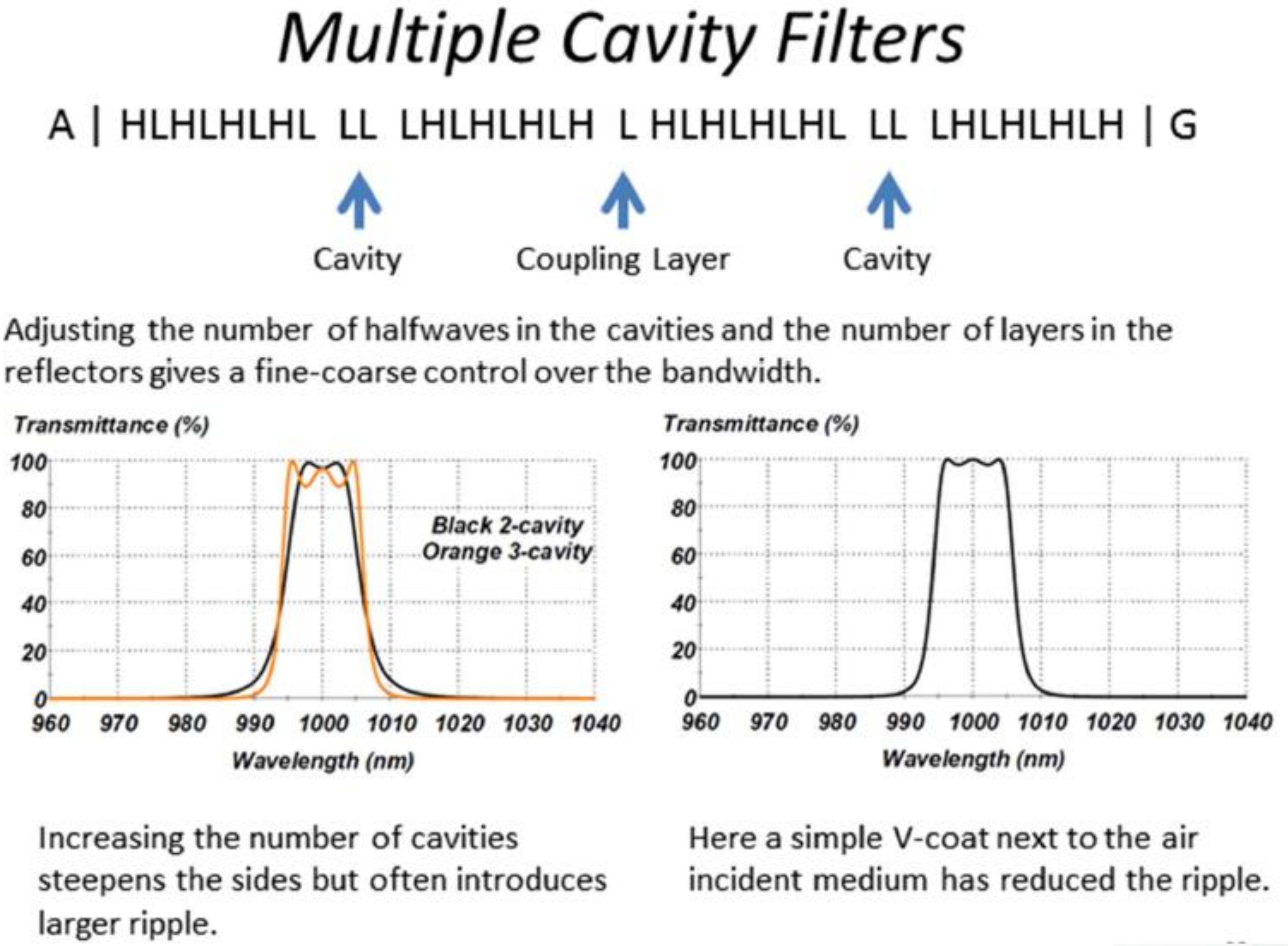
double cavity: two half-wave layers

Glass/HLHLHLHLH 2L HLHLHLHLH/Air

Glass/HLHL2HLHLH L HLHL2HLHLH/Air

19 layers **L**: SiO_2, **H**: HfO_2

Narrow-band filters



Multiple Cavity Filters

A | HLHLHLHL LL LHLHLHLH L HLHLHLHL LL LHLHLHLH | G

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.

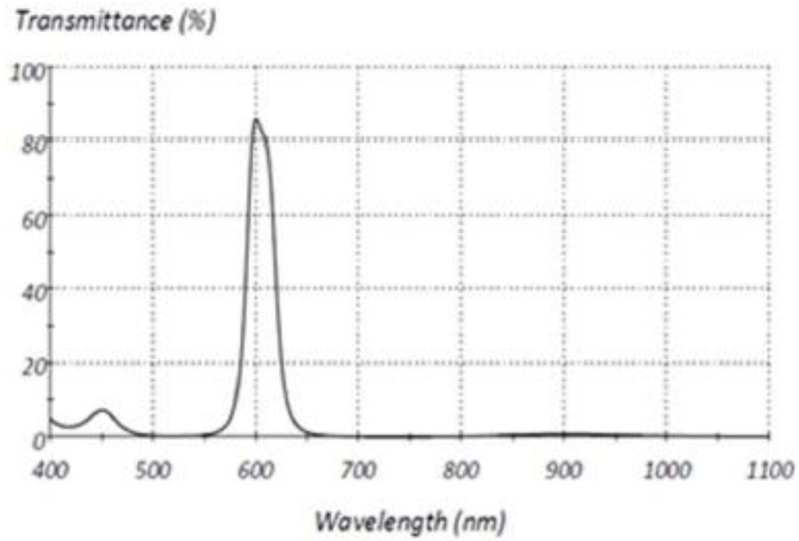
Here a simple V-coat next to the air incident medium has reduced the ripple.

H.A. Macleod: Optical Coating Design

Induced transmission filters

The induced transmission filter is obtained by canceling the reflectance of a metal layer by matching its refractive index with the surrounding media with the aid of dielectric stacks on both sides of the metal

Glass | HLHLHL 0.695H Ag (60nm) 0.695H LHLHLH | Glass



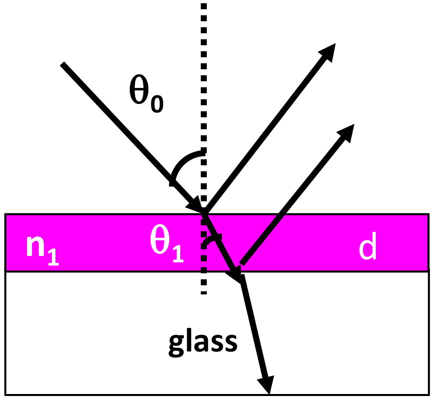
The advantage of this type of filter is the low transmittance out into the infrared because of the metal layer. This is difficult to achieve by other means.

H.A. Macleod: Optical Coating Design

The outband rejection improves with a higher ratio k/n of the metal layer

Oblique incidence

Snell's law : $\mathbf{n_0 \sin \theta_0 = n_1 \sin \theta_1}$

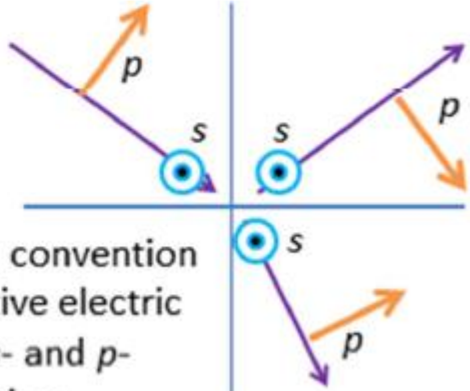


The index changes with the incidence angle

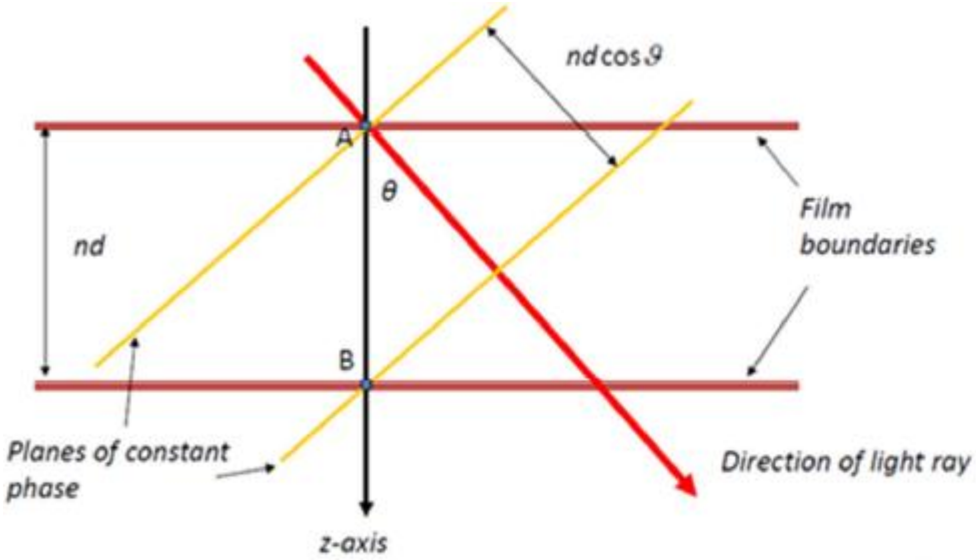
$\mathbf{n_1^s = n_1 \cos\theta_1, \quad n_1^p = n_1/\cos\theta_1}$

The path differences reduce

$\boldsymbol{\delta_1 = 2\pi n_1 d \cos\theta_1/\lambda}$ (phase thickness)



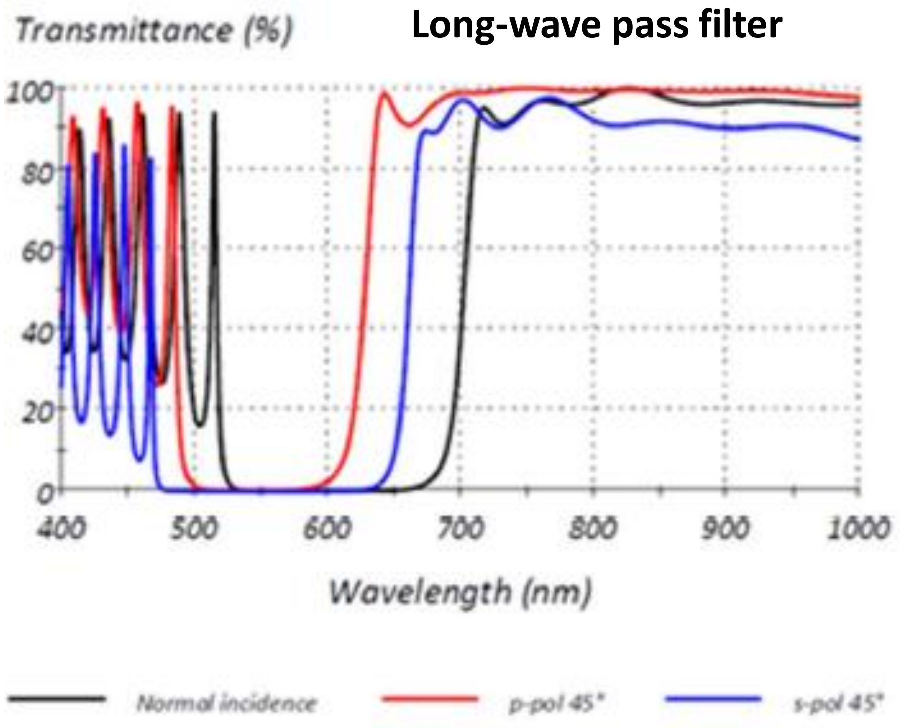
The sign convention for positive electric field in *s*- and *p*-polarization



Oblique incidence effects

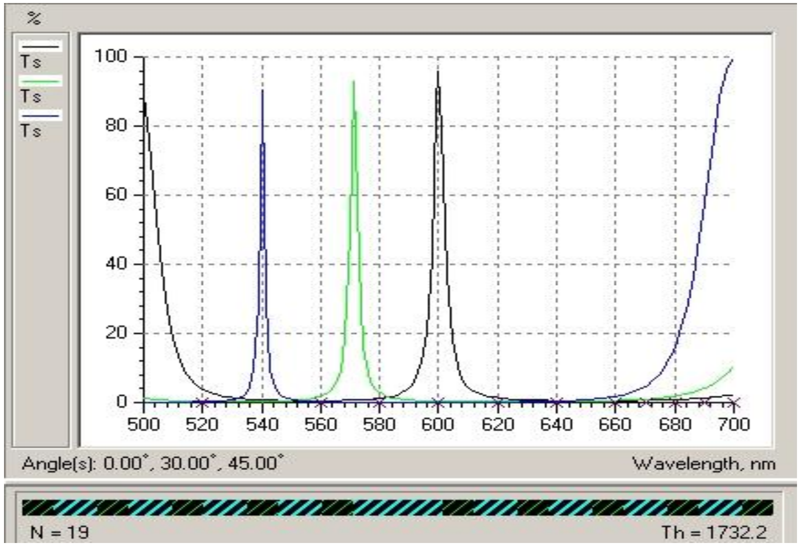
- ☐ Curve shift towards shorter wavelengths
- ☐ Curve modification depending on the polarization state (s o p)

Long-wave pass filter



Transmittance (%)

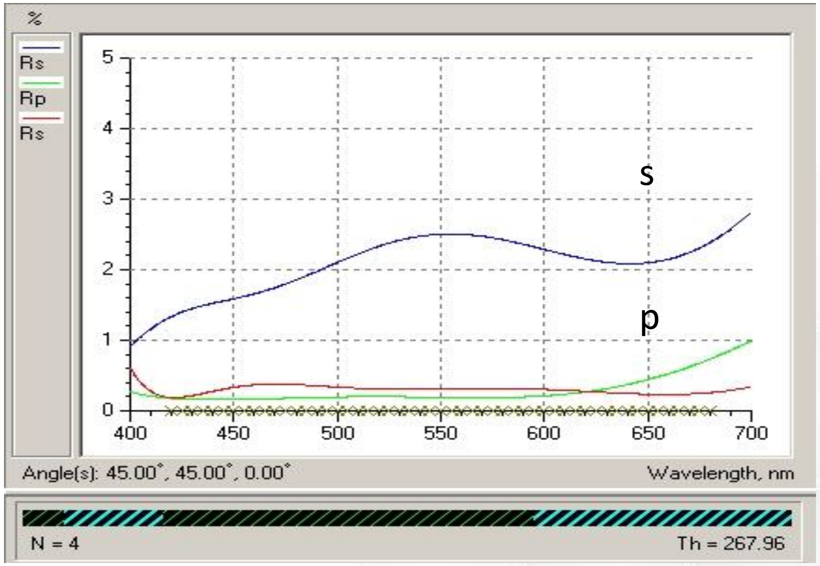
Fabry-Perot filter



θ_0 = 0°, 30°, 45° s-pol

Reflectance (%)

4-layer AR coating



θ_0 =0 θ_0= 45° s and p -pol

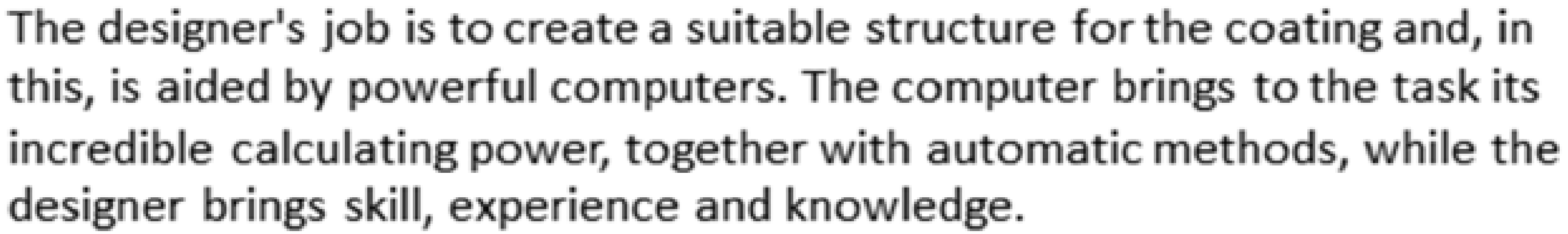
Optical Coating Design

Design methods

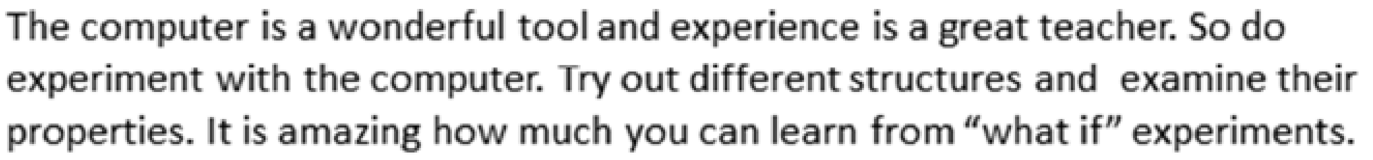
Two approaches are typically used to design optical coatings: optimization and synthesis.

In the first case an initial coating structure is refined, in the second case there is no need of a starting design.

H.Angus Macleod (2014):



The designer's job is to create a suitable structure for the coating and, in this, is aided by powerful computers. The computer brings to the task its incredible calculating power, together with automatic methods, while the designer brings skill, experience and knowledge.



The computer is a wonderful tool and experience is a great teacher. So do experiment with the computer. Try out different structures and examine their properties. It is amazing how much you can learn from “what if” experiments.

Design exercises by commercial software

Coating manufacturing

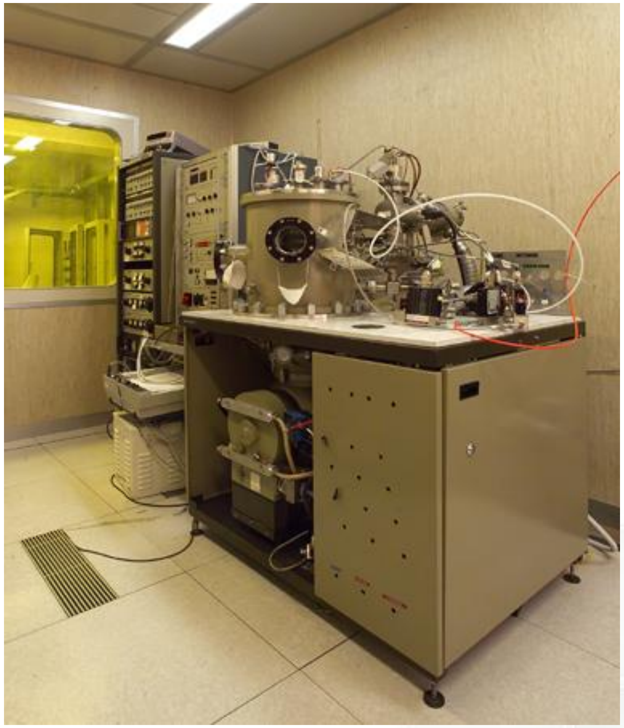
✓The effects of thickness (and index) variation can be simulated in advance to study the stability of the coatings against fabrication errors

✓During the design, the real material properties (not from the literature) should be used to avoid discrepancies with the experimental results

✓However the fabrication process is often more complicated than what appears from the theory, in fact not only optical properties must be taken into account

Classical PVD deposition methods

Electron-beam evaporation



Ion-beam sputtering