



SCHOTT
glass made of ideas



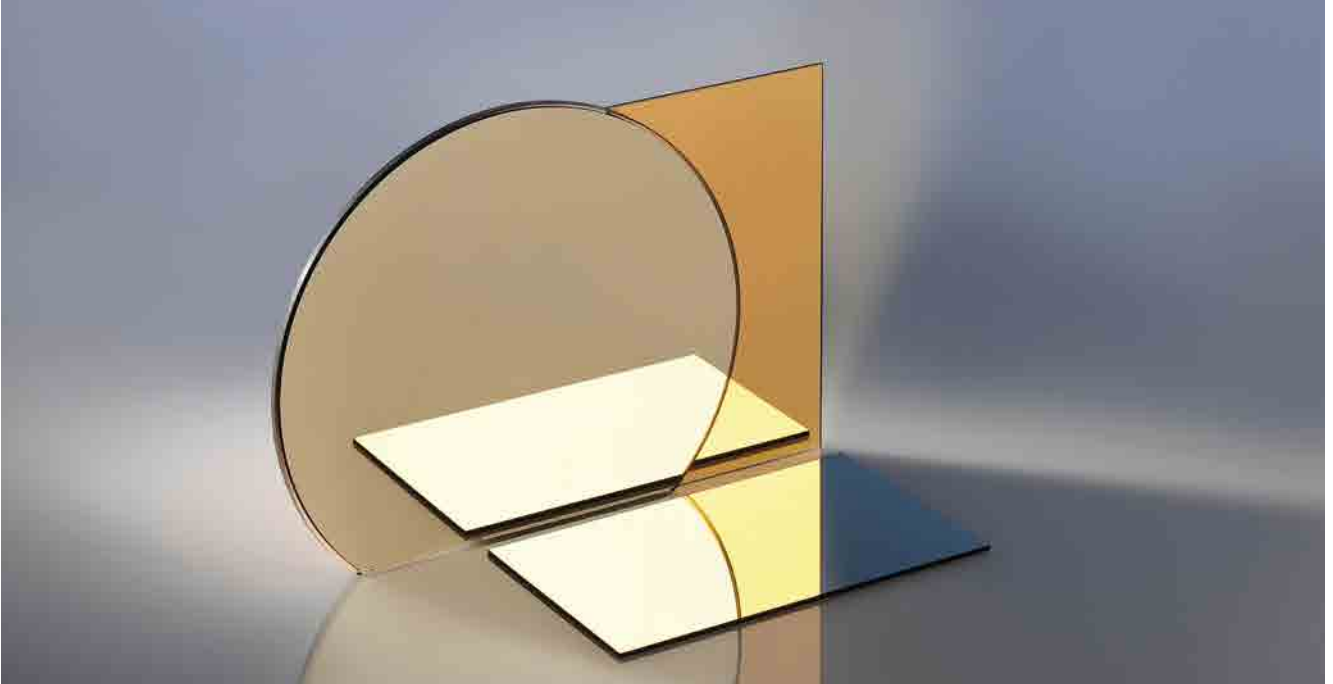
Interference Filters &
Special Filters

Description - 2015

SCHOTT is an international technology group with more than 125 years of experience in the areas of specialty glasses and materials and advanced technologies. With our high-quality products and intelligent solutions, we contribute to our customers' success and make SCHOTT part of everyone's life.

SCHOTT Advanced Optics, with its deep technological expertise, is a valuable partner for its customers in developing products and customized solutions for applications in optics, lithography, astronomy, opto-electronics, life sciences, and research. With a product portfolio of more than 120 optical glasses, special materials and components, we master the value chain: from customized glass development to high-precision optical product finishing and metrology.

SCHOTT: Your Partner for Excellence in Optics.



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1. Introduction

1.1 Foreword

Interference filters are used in various industries and enable challenging applications. Leveraging the function of various substrate materials in combination with special coatings, SCHOTT has been developing such filters since 1939.

While advancing its capabilities SCHOTT has continuously expanded its interference and special filter program.

These developments are reflected in this brochure. The content has been updated and new products based on our latest technologies have been added. Thus, SCHOTT's [Interference Filters & Special Filters Brochure](#) can be used as a reliable information source for system designers and optical engineers developing solutions for optical applications that meet a wide variety of different market needs.

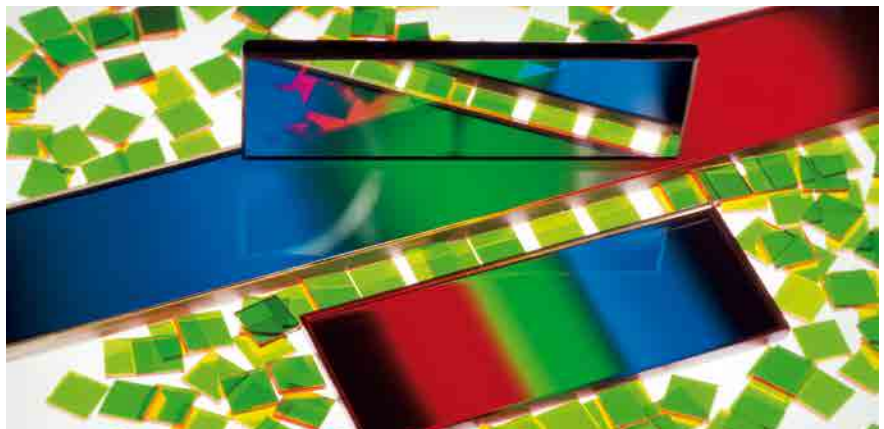
Interference filters and special filters are described in two different brochures. This brochure named "[Description](#)" informs about the most important criteria that pertain to the materials and characteristics of the filters. The other brochure named "[Properties](#)" covers additional technical information on each filter.

If any information not covered in this brochure is needed, please contact one of our regional sales representatives all over the world. Our experts will consult you and help in finding a solution for your challenge, since we believe the close relationship to our customers is key for successful work.

As we constantly strive to improve our products to your advantage through innovation and new technical developments, we reserve the right to change the optical and non-optical data in our [Interference Filters & Special Filters Brochure](#) without prior notice. The new brochures were assembled with the utmost care; however, we assume no liability in the unlikely event that there are content or printing errors.

The release of this brochure replaces all previous publications.

January 2015



VERIL filters showing various colors over length and green interference bandpass filters.

1.2 General information

SCHOTT Advanced Optics offers a wide variety of different interference filters for use in medical technology, analytics, consumer and security applications, whereby most of the offered filters are designed and manufactured according to customers' specifications.

SCHOTT first developed interference filters back in 1939, when Dr. Walter Geffcken, a SCHOTT researcher, filed a patent on "**interference filters**" (DE716153 and DE742463 – German patent office), a metal dielectric and all dielectric thin-film filter. In 1940, another patent was filed by Dr. Geffcken on "**coatings with reduced surface reflections**" (CH223344 – Swiss patent office), an AR coating.

Since then SCHOTT has not only built up extensive know-how and state-of-the-art technologies, but also a global production network capable of applying different coatings.

Interference filters use the interference effect to transmit or reflect certain spectral ranges of electromagnetic radiation by applying numerous thin-film layers to a substrate. This leads to various advantages resulting in an extensive use of interference filters in numerous applications and industries.

The main advantages offered are:

- Filter curves and forms can be designed in nearly all wavelength ranges, i.e. according to customers' specifications
- Steep filter edges, on both filter edges if needed
- Splitting of light power, if needed
- Splitting of polarization state, if needed
- A wide variety of different coatings from AR, conductive and mirror to all kinds of interference filter coatings

This brochure contains introductory information such as the explanation of the filters and environmental aspects (chapter 1) as well as specific information about interference filters. Chapter 2 deals with basic information on ADI- and MDI filters. Chapter 3 describes generally valid definitions and chapter 4 defines various properties such as angular or temperature dependence. Chapter 5 deals with coating processes. Chapters 6 to 8 cover topics like custom-made filters, applications and general comments.



Information is also available on the SCHOTT website:
www.schott.com/advanced_optics/interference-filters

Unless mentioned otherwise, all data shown in this brochure are valid at room temperature of 23 °C.

Upon request, the reference values can be specified more closely and the guaranteed values can be adapted to meet your requirements, if possible.

1.3 Explanation of interference filter types

The interference and special filter portfolio of SCHOTT includes the following types of filters:

- **Longpass interference filters** that only permit longer wavelengths to pass through
- **Shortpass interference filters** that only permit shorter wavelengths to pass through
- **Bandpass interference filters** that only permit a certain wavelength band to pass through
- **Neutral density thin-film filters** with a nearly constant transmission spectrum over the VIS spectrum to lower the light by a certain extent
- **Notch filters** or **bandblock filters** that block a certain wavelength band
- **Beam splitters** that split up a share of the incident light, e.g. 50%
- **Polarizing beam splitters** that split the 2 polarization states
- **Black chrome coatings** to avoid any reflections
- **AR coatings:** V-coating, broadband, multi-band, hard or scratch-resistant
- **Transparent conductive oxide** is a coating that transmits light and is electrically conductive
- **Linear variable filters** are bandpass filters that shift the center wavelength of the bandpasses over the length of the filter
- **Dielectric (laser) mirrors** reflect light with low absorption (and are thus well suited for use in laser applications)
- **Metallic mirrors** reflect light

1.4 Environmental aspects, hazardous substances, RoHS, ISO, REACH

SCHOTT Advanced Optics produces and distributes special materials and components in accordance with professional standards of our global Environmental, Health and Safety Management to prevent environmental pollution and to conserve natural resources and follows the procedures and philosophy of our global Quality Management System. Purchasing and handling of raw materials, the melting of batches, hot forming and coating is done strictly following established safety procedures and fulfilling requirements on material compliance.

All optical materials in this brochure comply with the requirements of the European Directive 2011/65/EU (RoHS). The optical materials featured in this brochure do not contain any mercury (Hg), chromium VI (CrVI) or the flame retardants PBB and PBDE whatsoever. Some of the optical filter glasses may contain lead or cadmium. They are in compliance with RoHS according to exemption 13b documented in ANNEX III of the directive 2011/65/EU.

In addition, all materials discussed in this brochure comply with the requirements of the European Regulation 2006/1907/EC (REACH: Registration, Evaluation and Authorization of Chemical Substances).

2. Basic information on interference filters

Interference filters leverage (as the name implies) the physical effect of the interference of light waves. This is illustrated in **Fig. 2.1** for the case of constructive and destructive interference.

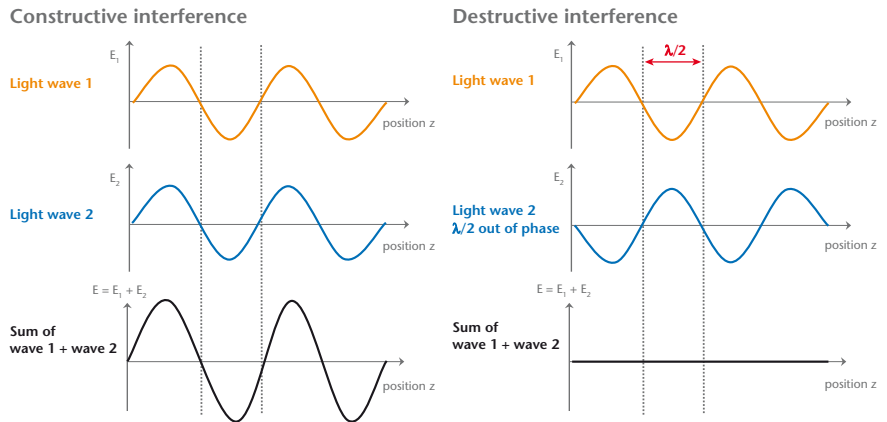
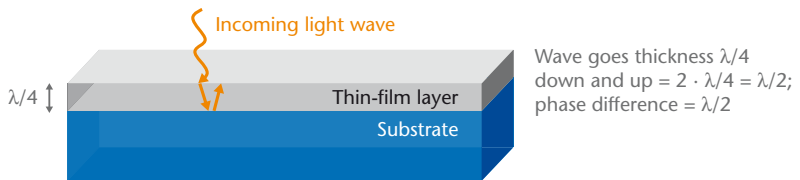


Fig. 2.1
Interference of two light waves for **constructive interference** (left): the two light waves are in phase and add to a superposition of both waves. In contrast, for **destructive interference** (right) one light wave is half a wavelength out of phase leading to light cancellation of the superposition.

As we can see from **Fig. 2.1**, if the two light waves are half a wavelength (or an odd number of half a wavelength) out of phase, then the superposition of both light waves leads to a cancellation of the resulting light if both waves have the same amplitude. It is precisely this light cancellation that is exploited for anti-reflective (AR) coatings, where no light is reflected (back), therefore all light is transmitted. Half a wavelength ($\lambda/2$) phase difference can be achieved by using a thin-film layer that is $\lambda/4$ thick, see **Fig. 2.2**.

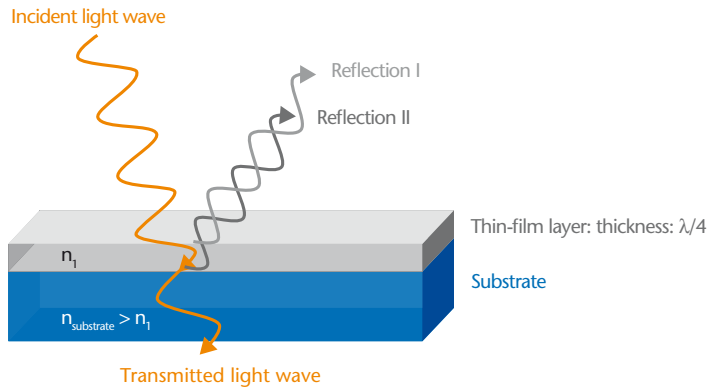
Fig. 2.2
A light wave entering a thin-film layer of thickness $\lambda/4$ is reflected backwards at the interface thin-film layer-substrate and thus travels the thickness $\lambda/4$ twice resulting in a phase difference of $\lambda/2$ (half a wavelength).



As shown in **Fig. 2.2**, a thin-film layer coating of thickness $\lambda/4$ generates a phase difference of half a wavelength ($\lambda/2$) for the wave traveling backwards. Therefore, no light is reflected back, thus all light must be transmitted. This is illustrated in **Fig. 2.3**.

Fig. 2.3

A thin-film layer of thickness $\lambda/4$ avoids any back reflection by destructive interference of the two reflected waves resulting in an anti-reflective (AR) coating.



As shown in Fig. 2.3, an incident light wave is partly reflected at the interface air-thin-film layer. A second partial reflection occurs at the interface thin-film layer-substrate. Due to the **thin-film thickness of $\lambda/4$** , the two light waves referred to as “Reflection I” and “Reflection II” are half a wavelength out of phase. Therefore, both waves interfere destructively and cancel each other out if they have the same amplitude. Thus, no light travels in the backward direction. Nevertheless, all light is transmitted, so this is an **anti-reflective (AR) coating**.

A thin-film layer thickness of half a wavelength ($\lambda/2$) results in a phase difference of a wavelength λ and no light will be canceled (see Fig. 2.1) in the backward direction. Thus such a **$\lambda/2$ thin-film layer** will behave as if it does not exist and part of the light is reflected off the substrate which is sometimes called an “absentee layer.”

An AR coating must fulfill two conditions: firstly a layer thickness of $\lambda/4$. In order to force both reflected light waves to have the same amplitude, the refractive index n_1 of the thin-film layer must fulfill the second condition:

$$n_1 = \sqrt{n_{\text{air}} \cdot n_{\text{substrate}}}$$

where n_{air} is the refractive index of the surrounding air and $n_{\text{substrate}}$ is the refractive index of the glass substrate.

Since the thickness “d” of an AR coating is defined by $d = \lambda/4$ and is thus directly proportional to the wavelength of the light, perfect cancelation is only possible at one wavelength. Or, in other words, an AR coating is wavelength dependent. For example, a glass with refractive indices $n_{\text{substrate}} = 1.52$ and $n_{\text{air}} = 1$ as the surrounding medium, would require a coating material with refractive index $n_1 = \sqrt{1 \cdot 1.52} = 1.23$. Since such a material is not available for a reliable coating,

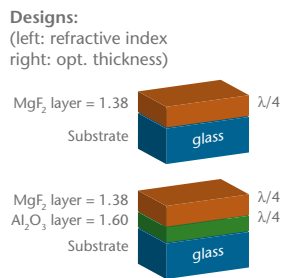
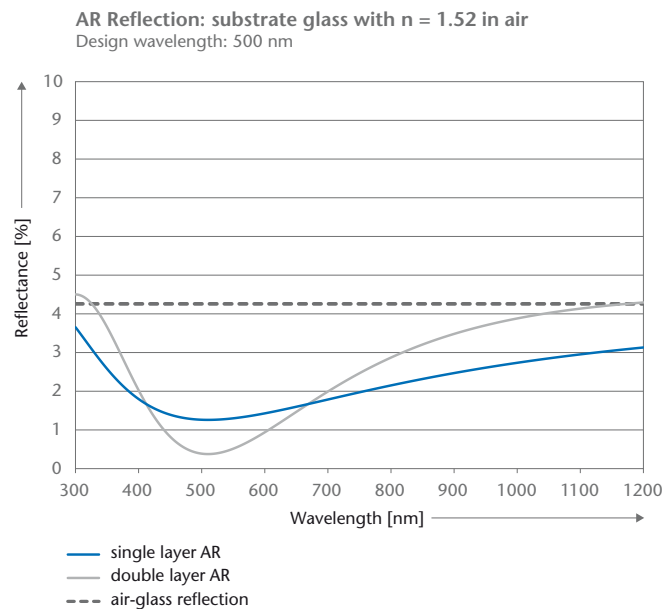


Fig. 2.4

A single layer MgF₂ AR coating reduces the air-glass reflectance from 4.3% to 1.3% at 500 nm. A double layer AR coating further reduces the reflectance to 0.4% on the expense of stronger wavelength dependency.



For further reduction of the residual reflectance, a second AR layer can be added. The first $\lambda/4$ layer must be made of a different material with a different refractive index, e.g. Al₂O₃ with $n = 1.60$ at 500 nm. If both $\lambda/4$ layers are made of the same material, then both layers add to a $\lambda/2$ absentee layer with no optical effect at 500 nm and the reflectance would again be 4.2% at 500 nm. Thus, the 2 layer AR coating consists of a medium refractive index $\lambda/4$ layer and a low refractive index $\lambda/4$ layer.

2.1 All dielectric interference filter (ADI filter)

As described, a 2 layer AR coating consists of a low refractive index $\lambda/4$ layer and a high refractive index $\lambda/4$ layer. As an abbreviation, this is referred to as LH, where L represents the low and H the high refractive index $\lambda/4$ layer. Such $\lambda/4$ layers are the **basic building blocks** of interference filters¹. For example the addition of two alternating H and L layers results in the abbreviation (HL)₂, where (HL)₂ means HL-HL design. This (HL)₂ layer design is shown on the left side in Fig. 2.5 together with the effect of many (HL) building block layers on the reflectance spectrum.

¹ For more details, please refer to Angus Macleod: "Thin-Film Optical Filters," 4th edition, CRC Press, New York 2010.

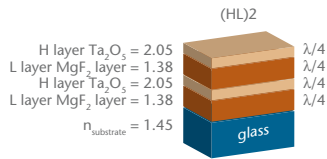
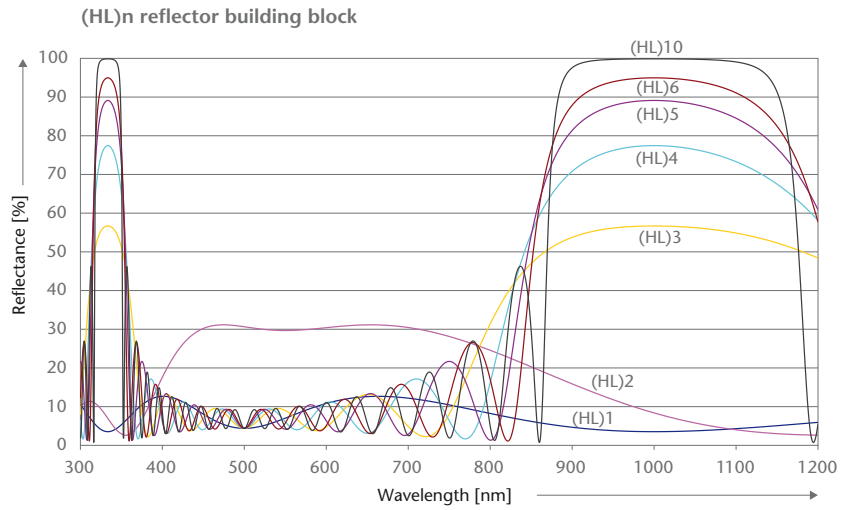


Fig. 2.5
 Reflectance spectrum of (HL) n layers from a simple (HL) building block towards an (HL)10 building block from 300 nm to 1200 nm. The design above shows the set-up of a (HL)2 layer design on a glass substrate with a refractive index of $n_{\text{substrate}} = 1.45$. The H layer has a refractive index of 2.05 made out of Ta_2O_5 and the L layer a refractive index of 1.38 made out of MgF_2 at a design wavelength of 1000 nm.



In order to visualize the interference filter made from an (HL)10 design, **Fig 2.5** is shown as transmittance spectra in **Fig. 2.6**. Such an (HL)10 design consists solely of dielectric layers with different refractive indices and is therefore called an **all dielectric interference filter (ADI)**.

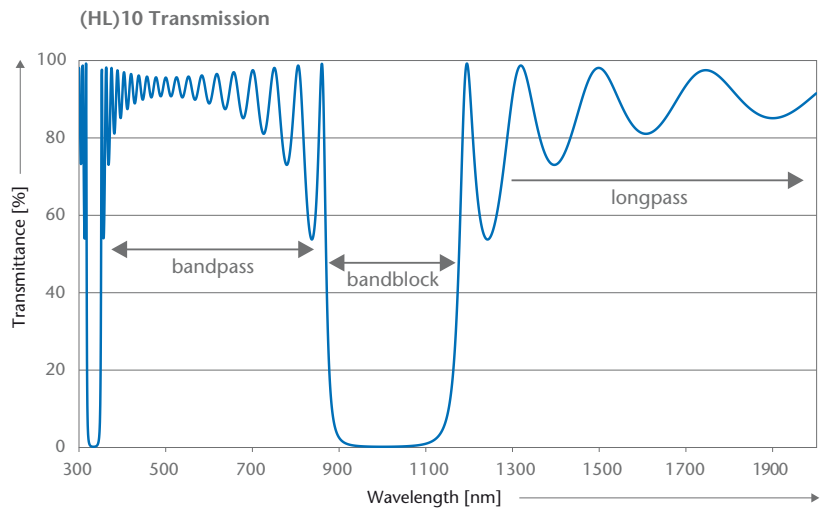


Fig. 2.6
 Transmittance spectrum of a (HL)10 design, also called all dielectric interference filter (ADI), from 200 nm to 2000 nm. Depending on the operating wavelength, a bandpass filter, band-block filter, or longpass filter will result. The design parameters are the same as in **Fig. 2.5**.

A narrow bandpass ADI filter can be produced by adding a $\lambda/2$ layer (absentee layer) inside the bandblock. The absentee layer allows the design wavelength to pass through the filter and to generate a narrow bandpass filter. For example, a simple bandblock is generated from an (HL)8 design where a glass of refractive index $n_{\text{substrate}} = 1.52$, H layer made of Ta_2O_5 and L layer made out of SiO_2 at 550 nm design wavelength were used. The narrow bandpass filter design with 2H as the $\lambda/2$ narrow bandpass layer is:

Air-(HL)4-2H-(LH)4 - glass.

The design is illustrated in Fig. 2.7.

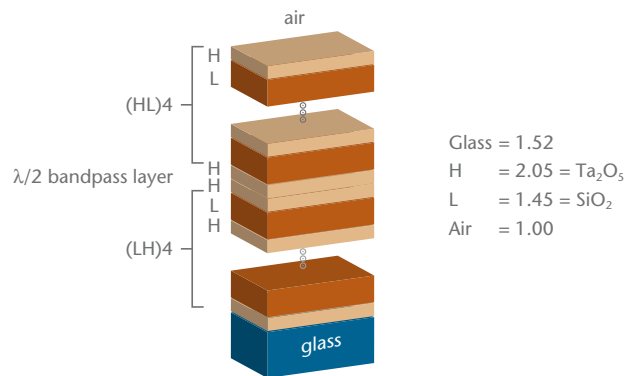


Fig. 2.7
Illustration of the narrow bandpass filter design with (HL)4-2H-(LH)4.

The (HL)8 bandblock and (HL)4-2H-(LH)4 narrow bandpass filter design generate the transmittance spectra shown in Fig. 2.8.

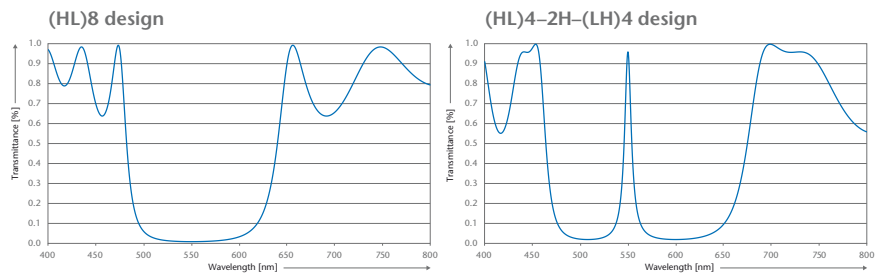


Fig. 2.8
Transmittance spectrum of an (HL)8 design (left) and a narrow bandpass filter design with a 2H bandpass layer (right) with design (HL)4-2H-(LH)4.

2.2 ADI filters with cavities

The narrow bandpass filter consists of the design (HL)4–2H–(LH)4, a single cavity. Adding a second cavity, i.e. (HL)4–2H–(LH)4 with a coupling layer L in between has the following design:

Air-(HL)4–2H–(LH)4–L–(HL)4–2H–(LH)4–glass.

This type of 2 cavity design improves the narrow bandpass resulting in steeper edges as well as a flatter passband, as can be seen in **Fig. 2.9**.

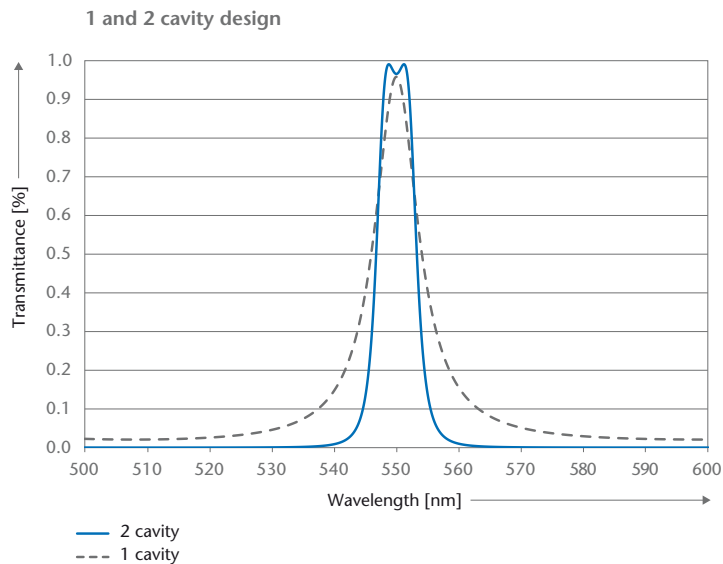


Fig. 2.9
Transmittance spectrum of an ADI filter from 500 nm to 600 nm for a single cavity design and a 2 cavity design. The 2 cavity design improves the narrow bandpass and has steeper edges as well as a flatter passband at 550 nm.

Increasing the number of cavities results in better performance of the narrow bandpass filter and changes the shape of the spectral transmittance curve from triangular to rectangular (see **Fig. 2.9**). At the same time, the curves get steeper and the inherent blocking outside the bandpass range increases.

The standard program of bandpass interference filters includes filters with two and three cavities. Filters with up to ten cavities and more are produced as special filters and broadband and blocking filters. Such custom-made filters make up a good share of the production program.

Examples of multi-cavity ADI filters are our DAX filters such as FITC-A/E.

2.3 Metal-dielectric interference filter (MDI filter)

Metallic layers reflect almost all light as we have seen with mirrors since the Middle Ages. The reflectance of aluminum is shown in Fig. 2.10.

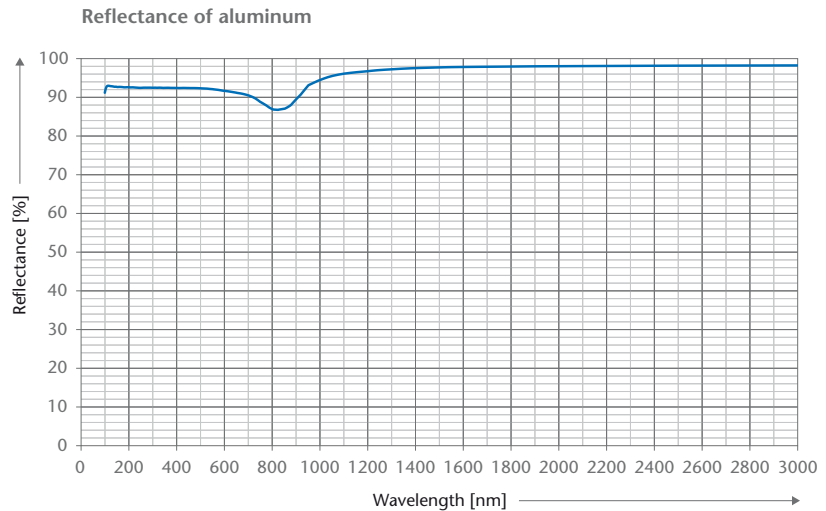


Fig. 2.10
Reflectance of aluminum².

Glass with a metal layer made of aluminum reflects light over the entire visible spectrum (380 nm to 780 nm) and deeply into the Infrared. Light in the UV range from about 150 nm to 300 nm is reflected (broad reflection in the UV is difficult to achieve with dielectric layers) and light in the IR with a wavelength of more than 1000 nm is also reflected as can be seen in Fig. 2.10. UV interference filters are thus one possible application of metal layers. Due to the broad reflectance spectrum, filters made of metallic layers have an inherent broad blocking spectrum.

Adding a second reflector spaced by a dielectric phase matching layer (also called spacer layer) generates a so-called Fabry-Perot resonator if the phase matching layer has the proper thickness (close to $\lambda/2$), see Fig. 2.11. For the design wavelength (with correct spacer layer thickness), the 2 waves with reflection r_1 and r_2 interfere constructively and the light will be transmitted. This assumes that the metallic layer reflects only part of the light. The top reflector can be made of (HL) n dielectric layers – compared with Fig. 2.5 where light with a wavelength ranging from around 900 nm to 1150 nm of a (HL)10 design is reflected nearly completely.

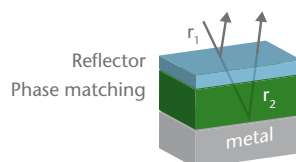


Fig. 2.11
A reflector separated by a phase matching layer on top of a metal layer generates a Fabry-Perot resonator.

² Edward D. Palik: "Handbook of Optical Constants of Solids," Academic Press, San Diego, USA, 1991.

Such a single phase matching layer design behaves like a narrow bandpass filter and its performance can be increased by adding more metallic layers separated by a phase matching (spacer) layer as it was described in section 2.2.

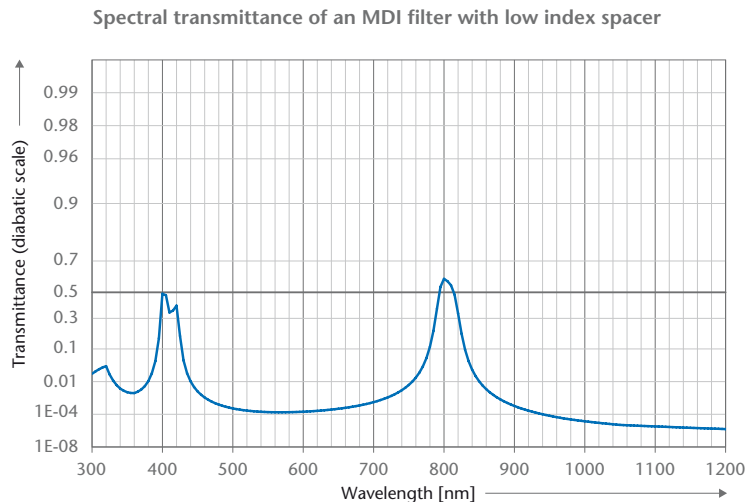
These filters are called **metal-dielectric interference (MDI) filters** and are mainly manufactured as bandpass filters. Their multilayer system consists mainly of thin, partially-transmitting metal layers separated by essentially absorption-free dielectric spacer layers. The thickness of the spacer layers mainly determines the spectral position λ_1 of the passband with the longest wavelength.

Further passbands are obtained at wavelengths of around $\lambda_k = \lambda_1/k$ ($k = 2, 3, 4, \dots$ in the case of low-index spacers³ e.g. in KMZ 50) due to the periodicity of a Fabry-Perot resonator. Wavelength λ_1 is also referred to as the first-order wavelength, λ_2 as the second-order wavelength, and so on. Because the refractive indices of the spacer layer materials are dependent on wavelength, the above equation can only be an approximation for the spectral position of higher order passbands, as illustrated in **Fig 2.12**.

MDI filters possess a broader inherent blocking range than non-blocked ADI bandpass filters with comparable bandpass characteristics. However, due to the absorption exhibited by the metal layers, MDI filters typically have lower maximum transmittance than ADI filters. The elimination of undesirable passband orders with MDI filters is achieved by means of additional blocking filters.

Examples of MDI filters in our program are KMD 12, DMZ 12 or KMZ 20 filters.

Fig. 2.12
An MDI filter curve (filter KMZ 35) with low index spacer shows the first-order wavelength of around 800 nm and the second-order wavelength of around 400 nm.



³ In the case of high index layers, further passbands are obtained for approximately $\lambda_k = \lambda_1/k$ ($k = 1.5, 2.5, 3.5, \dots$), e.g. KMZ 20 filters.



i-line bandpass filter with 160 mm diameter
transmitting light at a wavelength of 365 nm
used in lithography.

3. Definitions used with interference filters

Optical filters transmit a certain wavelength band, while other wavelength bands are being blocked. This selective transmittance of an optical filter is characteristic and therefore a quantitative measure of the optical filter. Filters typically consist of a plane parallel plate (plano-plano).

3.1 Spectral transmittance $\tau(\lambda)$

The spectral transmittance $\tau(\lambda)$, where λ is the wavelength in vacuum, is defined as the ratio of the transmitted (energetic) radiant flux $\Phi_{e,\text{transmitted}}$ to the incident (energetic) radiant flux $\Phi_{e,\text{incident}}$:

$$\tau(\lambda) = \frac{\Phi_{e,\text{transmitted}}}{\Phi_{e,\text{incident}}}$$

This is illustrated in **Fig. 3.1**.

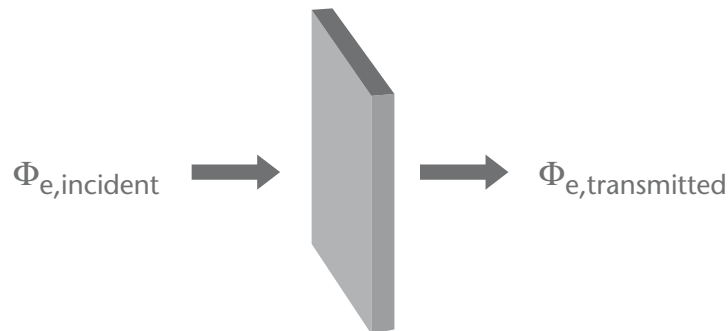


Fig. 3.1
Optical filter irradiated with incident radiant flux $\Phi_{e,\text{incident}}$ and the transmitted radiant flux $\Phi_{e,\text{transmitted}}$ for the definition of spectral transmittance $\tau(\lambda)$.

3.2 Spectral diabatie $\Theta(\lambda)$

It is advisable to use a derived form of the spectral transmittance, the so-called **spectral diabatie** $\Theta(\lambda)$. The spectral diabatie is defined as:

$$\Theta(\lambda) = 1 - \lg \left\{ \lg \left[\frac{1}{\tau(\lambda)} \right] \right\}$$

where “lg” denotes the logarithm to base 10. The diabatie form offers a significant advantage over the linear form: both the passband (at high transmittance) as well as the blocking band (with low transmittance) are stretched. Thus both the passband and the blocking band can be seen clearly, as demonstrated in **Fig. 3.2**.

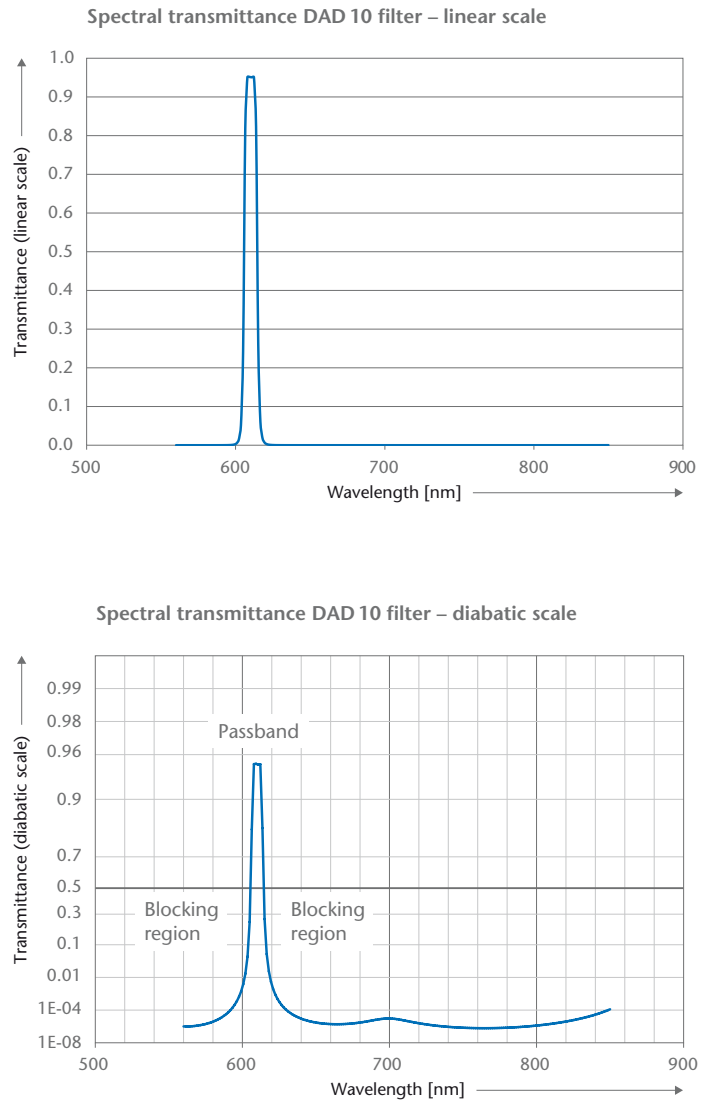


Fig. 3.2
 Linear (top) and diabatic (bottom) illustration of spectral transmittance for the same bandpass filter (DAD 10). The diabatic scale (bottom) stretches both the passband and the blocking region and ensures that the optical filter is characterized properly.

It should be noted that the definition of spectral diabatie for **interference filters** use spectral transmittance and a capital Greek theta (Θ) as a symbol. **Optical filter glass**, on the other hand, uses **internal** spectral transmittance as the definition with a small Greek theta symbol (θ).

3.3 Spectral optical density $D(\lambda)$

In some cases the quantitative characterization of a filter is described in terms of spectral optical density $D(\lambda)$. The relationship of spectral optical density to spectral transmittance is ruled by the equation:

$$D(\lambda) = -\lg \{ \tau(\lambda) \}$$

where “lg” denotes the logarithm to base 10. This form of optical density offers a special advantage in the blocking region. For example, instead of a blocking of $\tau = 10^{-5}$ at a certain wavelength, one obtains an optical density of $D = 5$.



Coated glass with a transparent conducting oxide, which is both transparent and electrically conducting.

3.4 Characterization of bandpass filters

Bandpass filters transmit a certain wavelength band, i.e. are characterized by having a range of high transmittance (passband) bounded both towards the shorter and longer wavelengths by ranges of low transmittance (blocking ranges), see Fig. 3.3.

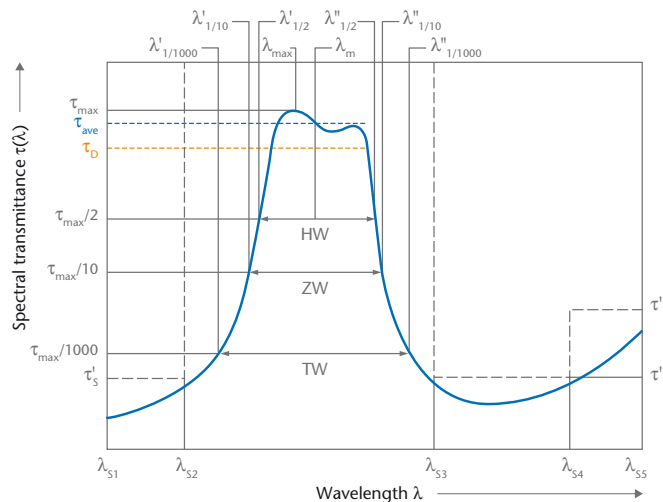


Fig. 3.3 A bandpass filter that transmits a certain wavelength band and shows characteristic values (defined below).

The most important properties of bandpass filters are defined using the following values (see also **Fig. 3.3**):

τ_{\max} :	Maximum value of spectral transmittance within the passband (peak transmittance)
τ_D :	Minimum value of spectral transmittance within the passband
τ_{ave} :	Mean (average) value of spectral transmittance within the passband (typically defined between two wavelengths in the passband)
λ_m :	Center wavelength: If $\lambda'_{1/2}$ and $\lambda''_{1/2}$ are the wavelengths at which spectral transmittance is $\frac{\tau_{\max}}{2}$ then $\lambda_m = \frac{\lambda'_{1/2} + \lambda''_{1/2}}{2}$
λ_{\max} :	Wavelength at which the filter reaches maximum spectral transmittance τ_{\max} (peak wavelength)
$\text{HW} = \Delta\lambda_{1/2}$:	Full width at half maximum (FWHM) = width of the transmittance curve at $\frac{\tau_{\max}}{2}$ If $\tau(\lambda'_{1/2}) = \tau(\lambda''_{1/2}) = \frac{\tau_{\max}}{2}$ then $\text{HW} = \Delta\lambda_{1/2} = \lambda''_{1/2} - \lambda'_{1/2}$
$\text{ZW} = \Delta\lambda_{1/10}$:	Tenth width = width of the transmittance curve at $\frac{\tau_{\max}}{10}$ If $\tau(\lambda'_{1/10}) = \tau(\lambda''_{1/10}) = \frac{\tau_{\max}}{10}$ then $\text{ZW} = \Delta\lambda_{1/10} = \lambda''_{1/10} - \lambda'_{1/10}$
$\text{TW} = \Delta\lambda_{1/1000}$:	Thousandth width = width of the transmittance curve at $\frac{\tau_{\max}}{1000}$ If $\tau(\lambda'_{1/1000}) = \tau(\lambda''_{1/1000}) = \frac{\tau_{\max}}{1000}$ then $\text{TW} = \Delta\lambda_{1/1000} = \lambda''_{1/1000} - \lambda'_{1/1000}$
$S_{\%}$:	Slope of filter in percent, defined by: $S_{\%} = \frac{\lambda_{80\% \text{ of peak}} - \lambda_{5\%}}{\lambda_{5\%}} \cdot 100$, where $\lambda_{80\% \text{ of peak}}$ is the wavelength at which the transmittance is 80% of τ_{\max} (correspondingly $\lambda_{5\%}$ wavelength where transmittance is 5% of τ_{\max}). The slope characterizes the steepness of the short wavelength edge and the long wavelength edge and thus 2 values are defined.
Q value:	$Q = \frac{\text{Tenth width}}{\text{Half width}} = \frac{\Delta\lambda_{1/10}}{\Delta\lambda_{1/2}} = \frac{\text{ZW}}{\text{HW}}$
q value:	$q = \frac{\text{Thousandth width}}{\text{Half width}} = \frac{\Delta\lambda_{1/1000}}{\Delta\lambda_{1/2}} = \frac{\text{TW}}{\text{HW}}$
τ_{5M} :	Mean (average) value of spectral transmittance within the blocking range. In the case of bandpass interference filters that are specified as having an "unlimited" blocking range (see also "Blocking range unlimited," section 3.6), the end of the sensitivity range of a commonly used detector is taken as the long-wave limit, when τ_{5M} is evaluated.
τ_S :	Upper limit for spectral transmittance within the blocking range
τ'_S, τ''_S etc.:	Upper limits for spectral transmittance within blocking ranges from λ_{S1} to λ_{S2} , from λ_{S3} to λ_{S4} etc.

3.5 Characterization of edge filters

Edge filters are characterized by having a range of high transmittance (passband) followed by a range of low transmittance (blocking range) or vice versa. There are two types of edge filters:

- **Shortpass filters** pass a shorter wavelength band i.e. have a range of high transmittance of shorter wavelengths than the blocking range.
- **Longpass filters**, on the other hand, pass a longer wavelength band (see Fig. 3.4), i.e. have a range of high transmittance of longer wavelengths than the blocking range.

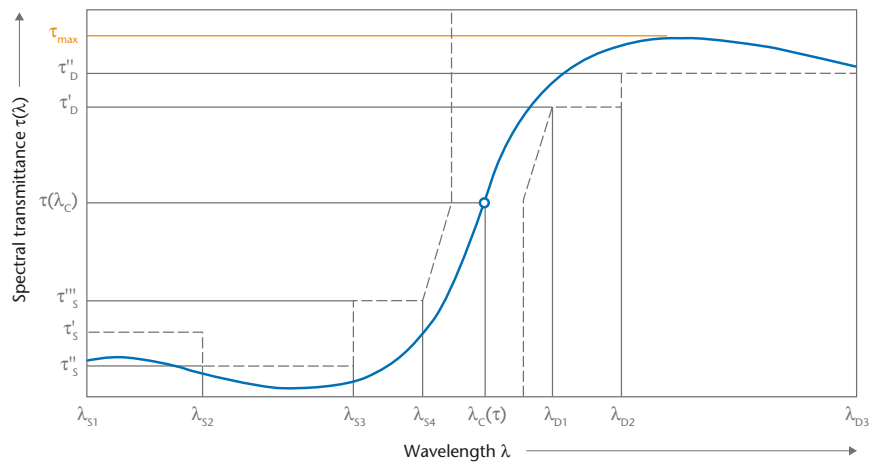


Fig. 3.4 A longpass filter as an example of an edge filter type and characteristic values.

The main properties of edge filters are defined by (compare with Fig. 3.4):

- τ_{max} : Maximum value of spectral transmittance within the passband (peak transmittance)
- λ_c : Edge wavelength, whereby spectral transmittance reaches a certain specific value, e.g. $\tau(\lambda_c) = 0.50$
- τ_{DM} : Mean (average) value of spectral transmittance within the passband
- λ_D : Minimum value of wavelength within the passband
- τ'_D, τ''_D etc.: Minimum values of spectral transmittance within the passband from λ_{D1} to λ_{D2} , from λ_{D2} to λ_{D3} , etc.
- τ_{SM} : Mean (average) value of spectral transmittance within the blocking range
- τ_S : Upper limit for spectral transmittance within the blocking range
- τ'_S, τ''_S etc.: Upper limit for spectral transmittance within blocking ranges λ_{S1} to λ_{S2} , from λ_{S2} to λ_{S3} , etc.
- $S_{\%}$: Slope of filter in percent, defined by: $S_{\%} = \frac{\lambda_{80\% \text{ of peak}} - \lambda_{5\%}}{\lambda_{5\%}} \cdot 100$, where $\lambda_{80\% \text{ of peak}}$ is the wavelength at which the transmittance is 80% of τ_{max} (correspondingly $\lambda_{5\%}$ wavelength where transmittance is 5% of τ_{max}).

- 3.6 Blocking range unlimited** This specification indicates that the short-wave blocking range extends from wavelengths below 100 nm up to the beginning of the passband. The long-wave blocking range extends from the end of the passband into the far infrared (wavelengths above 50 μm). Hence, for normal practical applications, the blocking range can be said to be unlimited.
- 3.7 Blocking range up to ...** This specification indicates that the short-wave blocking range extends from wavelengths below 100 nm up to the beginning of the passband. The long-wave blocking range extends from the end of the passband at least to the wavelength specified.
- 3.8 Blocking** Blocking is the additional attenuation of the radiation outside the filter's inherent blocking range by means of supplementary filters. Blocking is usually achieved by absorption and/or reflectance of the undesirable radiation.
- Blocking of the interference filters described in this brochure can mostly be arranged in accordance with customers' needs. It is therefore possible to increase the maximum transmittance within the passband or to reduce the thickness of the filter in certain cases. Filters without any blocking are also available upon request.
- 3.9 Angle of incidence** The angle of incidence is the angle between the optical axis of the incident beam and the normal to the surface of the filter facing towards the incident beam. Hence, if the beam is perpendicular to the filter surface, the angle of incidence is 0° .
- 3.10 Plane of incidence** The plane of incidence is the plane defined by the optical axis of the incident beam and the normal to the surface of the filter. Hence, at an angle of incidence of 0° , no plane of incidence can be defined, as the optical axis and the normal to the surface of the filter coincide.
- 3.11 Angle of aperture** In the strict sense of the word, parallel radiation (perfect collimated beam) does not exist; there are, however, almost parallel (quasi-parallel or quasi-collimated) beams that form a more or less open cone.
- The angle of aperture ϑ is **twice** the angle formed by the outer rays of the envelope cone of the incident beam and the optical axis (axis of symmetry) of the cone.
- Taking into account the spectral properties of interference and optical glass filters, and the accuracy normally expected in this area, radiation can be regarded as being "parallel" (quasi-collimated) as long as the angle of aperture is about 5° . Such angles are common in spectrometers used for determining the spectral transmittance of optical radiation filters.

3.12 Polarization

In the case of electromagnetic radiation, the electric field vector oscillates perpendicular to the vector of propagation. This property is a characteristic of transverse waves.

The electric field vector and the vector of propagation together define the so-called plane of oscillation. Unpolarized radiation has no preference for a particular plane of oscillation (the electric field vectors are statistically distributed); however, when all electric field vectors oscillate in the same direction, linear polarized radiation results. When parallel linear polarized radiation falls on an area, e.g. the surface of an interference filter, at an angle of incidence greater than 0° , two limiting cases are possible:

1. The electric field vector oscillates parallel to the plane of incidence. This is known as **P-polarization** or **TM polarization**.
2. The electric field vector oscillates perpendicularly to the plane of incidence. This is known as **S-polarization** or **TE polarization**.

In the case of a linear polarized radiation incident on a surface at an angle of incidence of 0° , these differences do not exist, as a plane of incidence cannot be defined.

The spectral properties of interference filters more or less depend on the degree of polarization of the radiation involved, especially if the angle of incidence is large.



Combination of interference filters and cemented optical filter glass (color glass).

4. Properties of interference filters

The next chapter describes the most important properties such as angular dependence, temperature dependence, radiation resistance, laser-induced damage threshold, and mounting & operating of interference filters.

4.1 Angular dependence

Interference filters are typically designed for a defined angle of incidence of the illumination beam. If the angle of incidence or angle of aperture changes, then the optical properties of the interference filter will change. These changes of optical properties depend, among other things, on the spectral position of the filter, the state of polarization of the radiation, the materials used for the layers and the design of the filter system as a whole. Even filters of the same type can exhibit different degrees of angular dependence due to the fact that the system design that depends on the spectral position of the filter must vary in order to comply with the spectral specification.

The transmittance wavelength or **edge position of interference filters is principally shifted towards the shorter wavelengths for increasing angles of incidence**. If the beam is parallel and the angle of incidence α is small (the acceptable range for α being dependent upon the filter in question), then the shift of wavelength $\Delta\lambda$ towards a shorter wavelength is approximately given by:

$$\Delta\lambda \approx k \cdot \sin^2\alpha$$

where k is approximately constant for a certain filter and state of polarization. Interference filters can be adjusted to the desired spectral position by tilting the filter.

The influence of angle of aperture also displaces the edge position of the filter towards the shorter wavelengths. In the case of unpolarized radiation with an angle of incidence 0° and an aperture angle ϑ that is not too large the shift is about the same as with parallel unpolarized radiation with an angle of incidence $\alpha = \frac{\vartheta}{4}$. In addition, in the case of bandpass filters, increasing angles of aperture lead to both a broadening of the transmittance curve as well as a decrease in maximum transmittance. These effects generally occur to a greater extent with filters of narrower band widths than with those of larger band widths.

For most applications changes in spectral values are practically insignificant up to angles of incidence of about 5° with parallel irradiated beams and up to an angle of aperture of about 20° at normal incidence, with the exception of bandpass filters with half widths of less than 5 nm.

Because many different behaviors of properties are possible due to the influence of angle of incidence and angle of aperture, (shift of λ_m and λ_c , changes in spectral characteristic, influence of polarization, etc.), no attempt will be made here to cover all of these aspects. However, we would be glad to assist and advise you, if any further information on your filter is needed.

4.2 Temperature dependence

The spectral values specified for interference filters are related to a temperature $T = 23^\circ\text{C}$ (room temperature). Depending on the type of the thin layers and the design of the entire layer system, the filters can exhibit different temperature dependences with regards to their spectral characteristics.

The integral of the passband curve and hence the signal received changes with temperature. Information on the change on the center wavelength or edge position is of special importance. Details are included in the “[Properties](#)” brochure.

The interference filters described in this brochure can be divided into five categories according to their temperature dependence:

1. Interference filters made by magnetron sputtering (MS)

Due to the compact structure of the layers by magnetron sputtering, which practically excludes the absorption of moisture from the environment, only very slight thermal dependence is demonstrated. The value is mainly dependent on the layer materials and substrate material due to the different thermal expansion of the materials and the temperature dependence of their refractive indices. Measurements made with edge filters within the range 23°C to 185°C resulted in typical temperature coefficients $\frac{\Delta\lambda}{\Delta T}$ of approximately -0.003 nm/K to $+0.005$ nm/K.

This type of interference filter is hence suited for applications where greater temperature changes are unavoidable but where changes in the spectral characteristics need to be minimized.

2. Interference filters with soft coatings by electron beam (EB) evaporation

This group comprises bandpass filters of the standard program, VERIL linear variable filters and the filter types KMD, KMZ, DMZ, MAZ, MAD, and DAD.

A shift towards the longer wavelengths usually takes place when temperatures rise. The temperature coefficient $\frac{\Delta\lambda}{\Delta T}$ is typically within the range $+0.007$ nm/K to $+0.03$ nm/K.

3. Interference filters with hard coatings by hot reactive electron beam (EB) evaporation

A shift towards the shorter wavelengths generally takes place when temperatures rise. In the temperature range 20 °C to 100 °C, the mean temperature coefficient $\frac{\Delta\lambda}{\Delta T}$ is approximately -0.15 nm/K. In the temperature range 100 °C to 250 °C, the mean temperature coefficient $\frac{\Delta\lambda}{\Delta T}$ is approximately -0.05 nm/K. This temperature dependence is generally acceptable for coatings that have broadband characteristics used in anti-reflective and mirror systems. Please see section 5 (Coating processes) to learn more about the advantages of this process.

4. Interference filters with hard coatings by ion assisted deposition (IAD)

Generally, a shift towards the longer wavelengths takes place as the temperature increases. In the temperature range 20 °C to 250 °C, the mean temperature coefficient $\frac{\Delta\lambda}{\Delta T}$ is approximately between -0.003 nm/K and $+0.005$ nm/K. This can vary depending on the choice of layer materials and substrate material.

Due to the variability of ion assistance, the thermal dependence can be influenced. If a customer needs a special temperature dependence within the range cited, we can make improvements on the basis of fixed substrate and layer materials, as the temperature dependence in this range is due to the thermal expansion coefficient of substrate and layer materials.

5. Interference filters with hard coatings by reactive ion plating (IP)

Due to the compact structure of the layers, which practically excludes the absorption of moisture from the environment, only very little thermal dependence is demonstrated. The value is mainly dependent on the layer materials and substrate material due to the different thermal expansion of the materials and the temperature dependence of their refractive indices. Measurements made with edge filters within the range 23 °C to 185 °C resulted in typical temperature coefficients $\frac{\Delta\lambda}{\Delta T}$ of approximately -0.003 nm/K to $+0.005$ nm/K.

This type of interference filter is hence suited for applications where greater temperature changes are unavoidable but where changes in the spectral characteristics need to be minimized.

4.3 Resistance to radiation

Intensive radiation, e.g. concentrated UV and powerful laser radiation, can lead to permanent changes of the optical properties of interference filters and optical radiation filters in general or even destroy them. The degree of distortion or damage depends, among other things, on the specific design of the filter in question and the nature of the radiation involved, especially as far as its intensity distribution (with respect to wavelengths, time and spatial geometry) is concerned. Radiation tests under controlled conditions have shown that the UV interference filters described in this brochure in general offer good resistance to intensive UV radiation.

Due to the large number of different radiation characteristics that can occur during application, however, these results cannot necessarily be transferred to every experimental situation. Hence, in many cases, reliable data with respect to resistance to radiation can only be obtained by testing under the conditions to be expected during the application envisaged.

4.4 Laser-induced damage threshold (LIDT)

High laser power can damage an interference filter due to the extremely high electric field of the incident laser power. This high laser power can lead to absorption-driven damage (via absorption by defect sites inside the coating that generates heat, melting, stress, etc.) or dielectric breakdown damage (where suddenly the insulating dielectric layer becomes conductive due to the high electric field). Therefore, coating layers and processes with extremely low attenuation are generally needed.

Continuous wave (CW) lasers emit constant power (steady state) and exhibit a different LIDT than pulsed lasers. For pulsed lasers, the energy density (in J/cm²) – also called fluence – is an important value for LIDT. Furthermore, peak power, pulse duration, and repetition rate should be known. Hence, the following information should be provided:

- Laser type: CW or pulsed laser
- Average power
- Beam diameter
- Wavelength of operation
- Pulse width (if a pulsed laser is used)
- Repetition rate (if a pulsed laser is used)

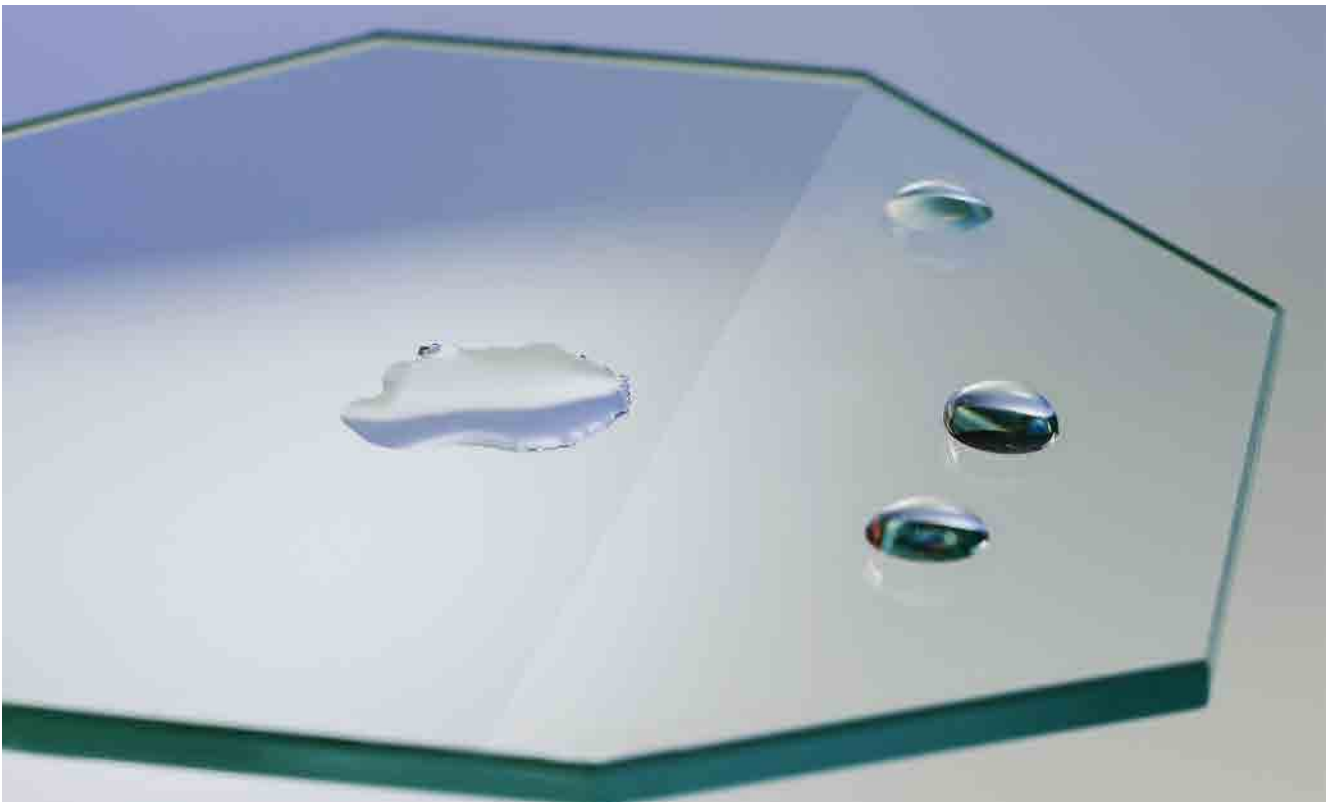
Based on this information and our experience, we will try to design and manufacture an appropriate optical coating that meets your exact needs.

4.5 Mounting and operating filters

Interference filters and optical filters in general should be fitted so that mechanical stress is avoided. The filters described here should not be exposed to temperatures higher than specified in the individual data sheets. To avoid unnecessary heating by radiation, filters with a reflective mirror side should be mounted with the mirror facing towards the irradiating light source.

The full filter area should be illuminated uniformly to avoid greater variations in temperature on the filter itself. The greater such temperature differences, the larger the danger that stresses will occur, which, especially in the case of cemented filters, can lead to permanent changes in the spectral specification and even breakage of the filter. The same principle applies to rapid changes in the filter temperature with respect to time.

Should applications be envisaged under conditions harsher than those described here, specific details should be included in your inquiry so that we can check whether these conditions can be fulfilled by using glasses with a higher degree of thermal stability or thermally tempered optical filter glasses.



Water drops on a uncoated (left) and hydrophobic coated (right) glass surface.

5. Coating processes

Interference coatings on SCHOTT's comprehensive materials are manufactured using different high vacuum coating deposition processes:

- Thermal or electron beam (EB) evaporation, cold or hot reactive
- Ion assisted deposition (IAD)
- Ion plating (IP)
- Magnetron sputtering (MS)

The choice of the respective process and manufacturing equipment to be used depends on considerations concerning layer material characteristics (refractive index, absorption, defect level, temperature dependence, etc.), process control (optical, quartz oscillator, time-power), substrate characteristics (dimensions, shape, temperature resistance) and, last but not least, costs (tooling, lot size, etc.).

Thermal or electron beam evaporation can be used for metals, soft layer materials (see below for details) and metal oxides on hot and cold substrates. This process is very versatile with respect to the choice of materials and change of processes during a production day. It also offers the most versatile tooling.

The so-called "soft" coatings are evaporated thermally or via electron beam evaporation on a cold substrate (*cold EB*). They offer the broadest choice of refractive indices, especially for low indices, and excellent transmission in the UV range. For this reason, these coating materials are used for UV and special filter designs that require certain refractive indices: e.g. bandpass filter designs with tailored full width at half maximum or polarizing beam splitters. Additional measures are taken to protect the layers from damage by handling or moisture. This is usually achieved by cementing the coated surface to an appropriate glass. The upper temperature limit for these filters is essentially determined by the nature of the optical cement being used.

Within certain areas of the UV spectrum, it is impossible to use optical cements due to the inherent absorption involved. In such cases, the coated substrates are fitted into appropriate mounts and protected by appropriate glasses.

In the hot reactive type of electron beam evaporation, metal oxide materials are deposited onto a substrate at elevated temperatures (300–350 °C) and oxygen is added during the process (*hot reactive EB*). This results in "hard" coatings that generally require no additional protection. Coatings manufactured using the hot reactive technique feature a columnar microstructure, which leads to a moisture take-up during the first 48 hours after manufacturing. This, in turn, results in a minimal spectral shift that can be reversed by baking in the coating. Depending on the substrate selected, interference filters with hard coatings made by hot reactive evaporation can be operated at temperatures of up to around 350 °C if the design and application can tolerate a small spectral shift (see section 4.2). This is generally the case with coatings that have broadband characteristics like AR systems and mirror systems.

Coatings made by using hot reactive electron beam evaporation can be produced nearly free of any contaminants. This is not the case when applying high energetic processes like ion assisted deposition, ion plating and magnetron sputtering.

Interference filters with hard layers by **ion assisted deposition, reactive ion plating** or **magnetron sputtering** are particularly well suited for applications where greater temperature changes or humidity are unavoidable but changes in the spectral characteristics are to be kept to a minimum. These hard coatings consist mainly of thin metal oxide layers and are very dense and resistant to external influences. Their microstructure is amorphous, which leads to practically no absorption of moisture from the environment. If an appropriate substrate is used (e.g. BOROFLOAT[®] borosilicate glass), these filters may be used at temperatures of up to approximately 350 °C.

In the process of **ion assisted deposition (IAD)** the layers evaporated by an electron beam are bombarded with an energetic ion beam of reactive ions (generally oxygen) during layer growth. The amount of ion assistance can be tailored to the desired film characteristics such as refractive index, density and stress in the coating.

In **reactive ion plating (IP)** the material is evaporated by an electron beam. In addition a highly energetic plasma beam is directed into the metal melt to result in a high fraction of ions in the gas phase. The particles that form a film are subsequently projected onto the substrate by bias-voltage applied to the substrate carrier. This results in a very dense film and high compressive stress, which leads to very durable and thermally stable coatings.

In a **magnetron sputtering (MS)** process a plasma is ignited in front of a magnetron cathode, that sputters (erodes) the target material bonded to that cathode. The particles that form the film traverse (cross) the plasma and deposit onto the substrate to form a dense and amorphous thin-film. This process can be performed with and without a reactive gas in combination with an additional plasma source to influence the layer stoichiometry. Metal layers as well as dielectric metal oxide layers can be deposited. The main advantage of magnetron sputtering is a very stable growth rate of the layers, which leads to a high degree of thickness control and the possibility of depositing many layers and immense overall layer thicknesses. Nevertheless, magnetron sputtered films can show non-negligible compressive stress especially in combination with greater layer thicknesses.

Magnetron sputtering enables the production of extremely hard, scratch-resistant AR-systems (e.g. on sapphire substrates), narrow bandpass filters or steep edge filters.

6. Custom-made filters

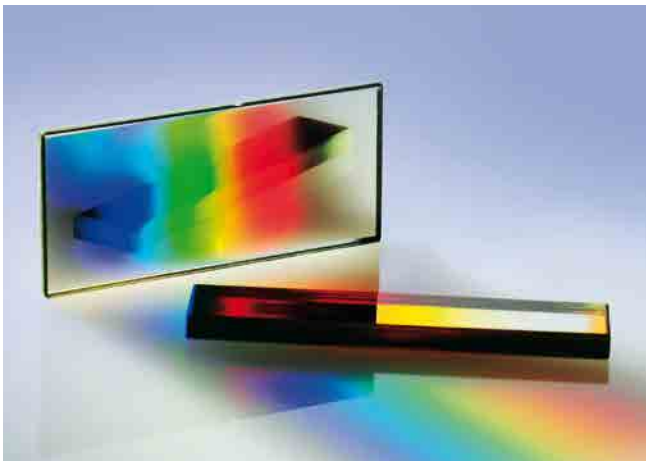
Many applications require interference filters with specific properties that are not available in our standard program. We would be more than pleased to discuss custom-made filter solutions with you.

The development and production of interference filters with specific properties that meet customers' specifications make up the greater part of our product line. It is also possible to have your own substrates coated on demand; however, we would like to point out that we are unable to assume any responsibility for possible breakage that might occur.

Custom-made filters are not only characterized by their specific spectral values but also by other parameters such as dimensions, special surface properties, thermal stability, increased stability against severe environmental influences, etc.

If you are in need of filters for your own particular applications with specifications that are not covered by our standard program, we would ask that you provide us with as many details as possible regarding the optical and non-optical properties you need in the form of technical drawings, for instance.

For the purpose of specifying your requirements, we also recommend filling out the questionnaires at the beginning of the "Properties" brochure. Please complete these and send them to us for checking and comments. We will then come back to you with either a specific cost quotation or an alternative suggestion.



A VERIL filter, bandpass filters with variable (over length) center wavelength.



A partly coated disc: a scratch-resistant AR coating (upper left) and an uncoated surface (lower right).

7. Applications

The following chapter gives a general overview of applications which utilize interference filters. Most of our interference filters are customized. Some applications of these filters are as follows.

Fluorescence spectroscopy typically requires steep bandpass filters and a dichroic beam splitter. The absorbed light coming from the light source is separated from the emission light from the sample under investigation with the help of steep bandpass filters.

Such steep bandpass filters are also used in **Raman spectroscopy**. If strong light is incident on a sample than the sample can scatter light due to the Raman-effect. This scattered light is typical for the sample under investigation. Raman spectroscopy requires steep edge filters, notch filters, and narrow bandpass filters.

Lithography uses for example UV-light at 365 nm (so-called i-line). SCHOTT offers narrow bandpass filters for applications in i-line steppers. The filter is coated with various layers and this tailored multilayer system is characterized with an outstanding transmission at 365 nm combined with a narrow spectral bandwidth and very good homogeneity of the spectral behavior throughout the usable filter area.

For **safety & security** applications such as digital surveillance cameras require IR cut filters that absorb the IR light. Only the visible light passes an IR cut filter which is often a combination of a blue filter glass and an additional interference filter as well as AR coating.

Medical & biotechnology applications require UV bandpass filters as well as edge filters to increase the signal-to-noise ratio of spectroscopic measurements.

In **analytic applications** a VERIL linear variable interference filter is used. Its central position of the center wavelength λ_m of the narrow passband changes constantly over the length of the filter.

In **industrial applications** our dielectric mirrors are used as laser mirrors due to the low absorption of this coating.

Astronomy applications require steep edge bandpass filters and very stable characteristics which can be met by our interference filters used in astronomical instrumentation.

8. General comments

Details on all of the interference and special filters described in this brochure including their optical and non-optical properties, are listed in the “[Properties](#)” brochure. Data qualified by approximation or not accompanied by tolerance values is to be understood only as guidelines (approximate values).

The following also applies to all individual descriptions of filter types: All spectral values given are based on room temperature of 23 °C in conjunction with quasi-parallel (= quasi-collimated) radiation (angle of aperture approximately 5°) and an angle of incidence of 0°.

The spectral (internal) transmittance curves shown are to be understood as general curves for orientation purposes only.

The measured spectral transmittance or reflectance curves (spectral transmittance $\tau(\lambda)$ linear from 0 to 1) for individual filters can be supplied upon request.

Specialized, custom-made filters make up the greater part of our product portfolio. If you are in need of filters with specifications that exceed those included in this brochure, we would suggest that you define these as clearly as possible. Here, we highly recommend that you fill out the **questionnaires** that can be found in the “[Properties](#)” brochure.



Black chrome coated substrates on top of a chrome-plated metallic surface.

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