Specifying Optical Thin Film

Most optical thin films are designed specifically for a particular application. Even for the same specifications, different vendor will have different process and design approach to meet the requirement. For example for a particular requirement, which is met by a 10 layers design, a 50 layers design can equally meet the requirement [1]. How many layers the eventual design should be, will depend on the process, the materials and the know-how of the coating vendor. As a customer, you may not need to be concerned about how many layers the design will be. The more important question you should be asking is whether it meets your performance and price targets.

What information should then be provided to the vendor?. Obviously, the more information you provide to the vendors, the easier it will be for them to understand your requirement and enabling them to make a prompt response to your requests. The performance specifications of the coatings consist of three types; one is the optical or spectral performance, the second is on the surface quality and the third is on the mechanical performance. There are many types of optical coatings and the information below gives a general guideline to the minimal information required by the vendor and to avoid over-specifying, which has potential cost implications.

Spectral Performance

The spectral performance specifies the reflection, transmission, absorption, angle of incidence, polarization, wavelength and laser damage requirements (for laser optics).

For spectral performance, one required parameter (irrespective of the types of coatings) is the substrate material. The coating design depends very much on the refractive index of the material. You will need to provide the vendor the refractive index of the material, and if not at least the name and supplier of the material. If these information are not available, you will need to provide the vendor with some samples of the material so that the refractive index and absorption properties of the material can be measured using an ellipsometer. This additional process will no doubt add extra cost to the coating development.

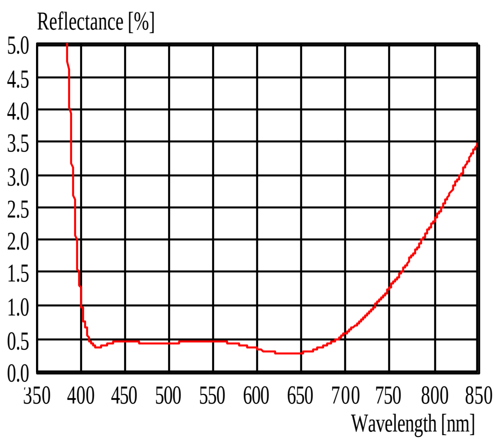
The geometry and shape of the substrate will also have implication on the coating design. The size and shape of the substrate will have implication on the piece part price as most optical coatings are batch processes and there is a maximum quantity per load. Since it is a batch process and there is always a set-up cost, the vendor may specify a minimum order quantity (MOQ) in order for the process to be run cost-effectively. The geometry of the substrate will also allow the vendor to work out the tooling, handling and packaging costs.

Anti-Reflective (AR) Coatings [2]

The required parameters to specify the spectral performance are:

(a) the wavelength (in nanometers) of interest
(b) the absolute (*R* %) reflectance or reflectance at ALL wavelength of interest for one-sided or two-sided coating
(c) the average (R_{ave} %) reflectance (averaging *R* over the wavelength of interest) for one-sided or two-sided coating
(d) refractive index of substrate
(e) the absolute (*T* %) and average (T_{ave} %) transmittance, if the substrate absorbs light
(f) the angle of incidence (*AOI*, assumed 0^o if no value is provided)

The *AOI* has an implication on cost. If a big range of *AOI* is required, it will require more layers of coatings and hence the cost will be higher.



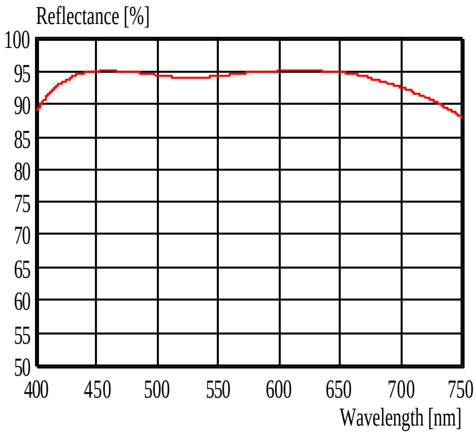
AR coating with *R* < 0.5% from 420nm to 680nm using glass substrate. Note that R_{ave} is lower than 0.45% for the wavelength of interest.

Reflective (Mirror) Coatings

The required parameters are quite similar to AR coatings:

(a) the wavelength (in nanometers) of interest

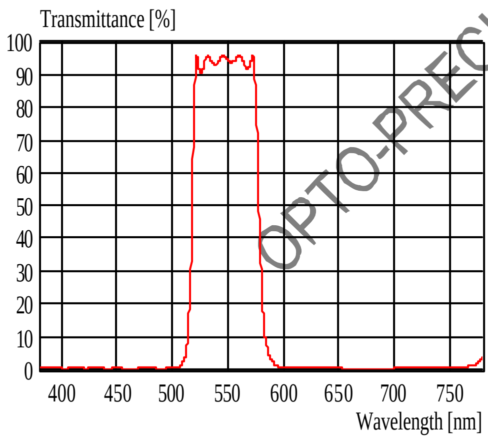
(b) the absolute (R %) reflectance
(c) the average (R_{ave} %) reflectance
(d) refractive index of substrate
(e) AOI



Enhanced aluminium (glass) mirror with R_{ave} > 90% from 450 nm to 750 nm.

Filter Coatings

Filters are usually flat substrates. It can also be cylindrical or cubic in shape. For filter coatings, the specifications are more elaborate.



T < 1% at 390nm to 485nm
T = 50% at 518nm +/- 7nm
T > 85% at 550nm to 565nm
T = 50% at 578nm +/- 7nm
T < 1% at 610nm to 760nm
AOI = 0^o
Substrate = glass

For the green filter above, we are using absolute transmission, T, to specify the spectral curve but note that we had broken down the spectral curve into a few sections with different transmittance values. The area of high transmittance is known as the passband and the area of low transmittance is the stopband.

In addition to the transmittance values, the rate of drop from high to low transmittance is also important. Hence, the wavelength at 50% transmittance is another parameter that needs to be specified. How steep the curve (filter edge) is going to drop will depend on this value. Generally, the steeper the curve the more layers of coatings are required and hence higher costs. The other parameter that will have impact on cost is the tolerance of the wavelength at 50% transmittance. In this case it is +/- 7nm, which is easily achievable with high-end commercial coaters. As a guide line, 1% to 2% of the wavelength is the norm. This parameter is limited by the process/machine capability. The filter edge is known to shift from each production run to another. Even within the same run, the value may differ for substrates on different positions on the substrate holder [2]. The tighter the tolerance, the lower will be the yield and hence the higher will be the costs.

Instead of the wavelength at 50% transmittance, the Full Width Half Maximum (FWHM) values are sometimes specified. This is half the maximum transmittance. For example, if the T_{max} is 80%, the FWHM is at 40% transmittance.

The average transmission, T_{ave}, may also be an important parameter for both the passband and the stopbands. The maximum peaks, T_{max}, in the stopbands are also normally given. The average transmission values in the stopband will also have cost implications. For the given green filter example, the number of coating layers is about 30. If the T_{ave} for the stopband is to reduce, say to below 0.01%, the number of layers required can increase to above 100. The rule-of-thumb is that the higher the number of layers, the lower will be the yield, since failure in any layers can result in the filter not meeting the specifications.

In summary, the parameters required to specify a filter are:

(a) T, T_{max} and T_{ave} of the wavelength of interest
(b) The wavelength at 50% transmission and the tolerance
(c) Refractive index of substrate
(d) *AOI* (usually 0 or small value)
(e) Polarized Transmission (*s* or *p*), T_p and T_s

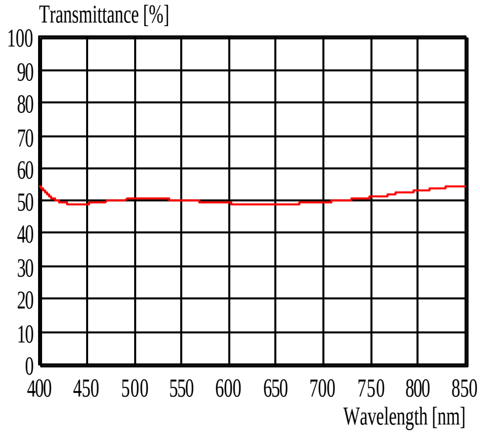
The polarization is important for certain filters.

Beam Splitting Coatings

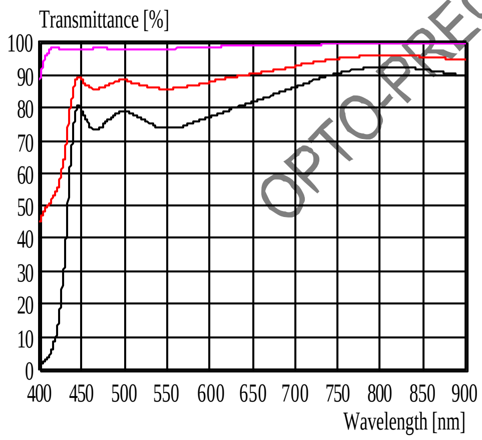
Beam splitting coatings can be considered as a special type of filters but usually they have high *AOI* e.g. 45^o. Beam splitters come in many shapes depending on the optical design e.g. cubes, flat parts or combinations. Some are designed to allow light of certain wavelength to be transmitted and light of another wavelength to be reflected. Some are half-mirror, i.e. allowing 50% of the light to be transmitted and the rest reflected. The common parameters required are:

(a) *T*, T_{max} and T_{ave} (*R*, R_{max} or R_{ave}) of the wavelength of interest, the polarization and the *AOI*
(b) Refractive index of substrate

The following are two beam splitter examples:



T_{ave} = 50% +/- 5% at 420nm to 800nm
R_{ave} = 50% +/- 5% at 420nm to 800nm
At *AOI* = 45°.



T (average of *s* and *p*) > 90% at 700nm to 900nm
T (average of *s* and *p*) > 75% at 450nm to 650nm
At *AOI* = 45°.

Measurement Of Spectral Curve

The spectral curve is measured using a spectrophotometer. Depending on the type of spectrophotometer, the measurement piece needs to be of certain size and of flat shape. Not all optical components come in this size and shape. For parts, which could not be placed directly onto the spectrophotometer for measurement, a witness piece is used. A witness piece is usually a flat piece made from the same substrate material as the target component. It is placed in the same chamber together with the target components during coating and the coating properties of the witness piece should be representative of the coatings on the target components.

Spectrophotometer is a sensitive piece of equipment and needs periodic calibration. The wavelength range and the resolution determine the capability of the equipment. For example, if we need to measure the shift of the filter edge (described earlier) down to a few nanometers, the resolution of the spectrophotometer has to be one-tenth to one-twentieth of that value to give meaningful measurements.

Surface Quality

Cosmetic surface quality describes the level of defects that can be visually detected. These cosmetic defects not only affect the appearance, they also scatter light.

The most commonly used and widely accepted standards for specifying surface quality is the U.S. Military Surface Quality Specification, MIL-0-13830A[4]. An alternative specification, which is widely used in Europe, is DIN3140[5].

The MIL-0-13830A standard cover surface defects such as scratches, digs, grayness, edge chips and cemented surfaces. Digs are small pits or craters on the polished optical surface. The scratch/dig number is normally specified for optical substrates. The first number represents the allowable maximum scratch visibility in ten thousandths of a millimeter and the second number refers to the maximum dig diameter in hundredths of a millimeter. For example, a 80/50 scratch/dig number does not allow any scratches that are longer than 8 µm or any dig which is larger than 0.5 mm diameter. 80/50 represents a commonly accepted cosmetic standard. 60/40 represents an acceptable standard for most scientific research applications and a 10/5 number represents very precise requirements.

It should be mentioned that the inspection for defects is by visual comparison with standard scratch/dig standards. The appearance of the scratch can depend on the component material and whether there is presence of coatings; some defects are difficult to see without AR coatings.

The coating process itself can contribute scratches and digs. Coating defects can be in the form of scratches, voids, pinholes, overcoated particles or stains. The defects can be due to handling and contamination of the substrates during the coating process. Coating defects are allowed if their size is within the stated scratch/dig number. Coating defects are counted separately from substrate defects.

Mechanical Properties

Achieving the spectral specifications only is usually not sufficient. The coatings also have to be mechanically robust to withstand the handling during normal usage and exposure to environmental factors. There are a few standards which are commonly referred to. They are:

(a) Humidity resistance: MIL-C-675A[6]
The coated part is subjected to 95% relative humidity for at least 24 hours at a temperature of 49 ^{o}C. The parts are then inspected for spectral and physical degradation.

(b) Humidity resistance: MIL-STD-810C[7]
This is a ruggedised environmental test, where the parts are exposed to high humidity while undergoing temperature cycling. The parts are then inspected for spectral and physical degradation.

(c) Abrasion resistance: MIL-C-675A
This test is for parts that will be subjected to abrasion during usage. A standard rubber-pumice eraser is used to rub from one point to another on the test article for 20 complete cycles (40 strokes) with a constant force of 2.0 to 2.5 pounds applied. The length of the stroke shall be about 3 diameters of the eraser. The eraser shall be held at a right angle to the rubbing surface. The test article is then cleaned, dried and inspected visually. The coating passes if there is no visible abrasion and damage to the coating.

(d) Coating hardness: MIL-M-13508C[8]
This test is less harsh than the abrasion resistance test. It is for parts that are not directly expose to abrasion or rubbing actions during usage, e.g. parts within an enclosure. The test article is rubbed with a clean piece of cheesecloth with a constant one pound force applied. The rubbing is to be over the same path and for a minimum of 25 complete cycles (50 strokes). The test article is then examined visually for scratches or coating damage. The coating passes the test if no such defects are found.

The picture above shows the rubbing test being done using cheesecloth and a special tool with calibrated 1 pound force.

(e) Coating adhesion: MIL-M-13508C
The test is performed by pressing a cellulose (or cellophane) tape (typically from 3M) firmly onto the surface of the test article and then removed slowly and evenly at an angle which is normal to the coated surface. The coating passes the test if the coating is not removed.

The tests above assumed that the optical parts are large enough for the described tests to be carried out. If the parts are too small, it is an accepted practice to use a witness piece instead.

The specifications, measurements and tests mentioned to specify optical coatings are by no means exhaustive. New measurements and test methods are continuously being introduced and the information given here is only meant to be used as a guideline.

References:

[1] “Optical thin film coatings”, *Opto-Precision Application Note A001*.
[2] “Optical thin film applications”, *Opto-Precision Application Note A003*.
[3] “Ion-assisted deposition”, *Opto-Precision Application Note A002.*
[4] “Optical components for Fire Control Instruments: General specification governing the manufacture, assembly and inspection”, *MIL-O-13830A*
[5] “Optical components form errors”, *DIN3140*
[6] “Anti-reflection coatings for glasses”, *MIL-C-675C*
[7] “Standard for environmental engineering”, *MIL-STD-810C*
[8] “Front surface aluminium mirrors”, *MIL-M-13508C*

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