Semrock Technical Note Series:

Measurement of Optical Filter Spectra

Semrock a Unit of IDEX

The Standard in Optical Filters for Biotech & Analytical Instrumentation

Measurement of Optical Filter Spectra

1. Introduction

Optical filters play an important role in enabling applications such as fluorescence microscopy and Raman spectroscopy. In these applications there are two distinct types of beams: the illumination (or excitation) beam and the signal (or emission) beam. Not only are these beams spectrally distinct, but also they differ significantly in their intensity – the signal beam can be a million times (or more) weaker than the illumination beam. Therefore, the ability of filters to selectively transmit desired wavelengths of light while blocking unwanted light is critical. The performance of such filters is determined by their spectral characteristics, including transmission efficiency of the signal and attenuation (or blocking) of the illumination light and undesirable emission wavelengths. In particular, often it is critical for filters to transition from deep blocking to high transmission over a very short wavelength range, leading to steep and deep spectral edges. However, due to limitations of standard metrology techniques, the measured spectral characteristics of thin-film interference filters are frequently not determined accurately, especially when there are steep and deep edges. As a result, it is difficult to ensure sufficient system-level performance without a lot of trial-and-error experimentation with the filters. In this article we explore limitations to accurate filter spectrum measurements with standard metrology techniques, and show how these limitations can be managed by a better understanding of the limitations as well as more sophisticated measurements when necessary.

2. Conventional approach for the measurement of filter spectra

It is well known that in order to effectively suppress undesired light, the blocking specification of an optical filter must be typically many orders of magnitude higher than that of transmission. Optical Density – or OD, as it is commonly called – is a convenient tool to describe the transmission of light through a highly blocking optical filter, or one with extremely low transmission. OD is simply defined as the negative of the logarithm (base 10) of the transmission, where the transmission varies between 0 and 1; that is $OD = -\log_{10}(T)$.

The actual blocking provided by a filter is determined not only by its designed spectrum, but also by physical imperfections of the filter, such as pinholes generated during the thin-film coating process, dirt and other surface defects, or flaws in the filter mounting. Pinholes can allow light to pass through the filter unblocked – a single 10 μm pinhole (that penetrates completely through the coating) limits the blocking of a 10 mm diameter beam to at most OD 6, regardless of the designed level of blocking of the filter spectrum. Other surface and mounting imperfections can cause scattered light that “leaks” through the filter due to a shift of the spectrum to a region of high transmission for scattered light at high angles of incidence, or via unblocked paths near the edges or mounting. Therefore, it is important to evaluate the blocking performance of filters after they have been fully manufactured into finished products.

Generally commercially available spectrophotometers are used to measure the transmission and OD spectral performance of optical filters. However, these instruments can have significant limitations when the optical filters have high edge steepness and/or very deep blocking.

The principle of operation of a typical spectrophotometer is illustrated in Figure 1. A monochromator contains a diffraction grating to disperse light from a broadband source (usually a quartz-tungsten-halogen (QTH) or arc lamp) into a range of angles, and then uses an adjustable slit to select a narrow band of wavelengths. This quasi-monochromatic probe beam is then directed toward the sample (test) filter. In a dual-beam spectrophotometer (as shown here), either a beamsplitter is used to split the probe beam into *reference* and *measurement* beams, or the light is alternated in time between the reference and measurement paths at a relatively high rate. The reference beam goes directly to the detector, though it might be attenuated with a calibrated neutral density filter depending on the blocking level of the sample filter. The measurement beam passes through the sample filter and then impinges on the detector. The filter spectrum, or its transmission (or blocking) specification as a function of wavelength, is established from the ratio of the signals from the two beams as the wavelength is scanned over a broad range. The spectrum can also be obtained from a single-beam spectrophotometer, except in this case the reference signal is generated without the sample filter in the light path and then the measurement signal is generated by inserting the sample filter into the light path (as in Fig. 4 below).

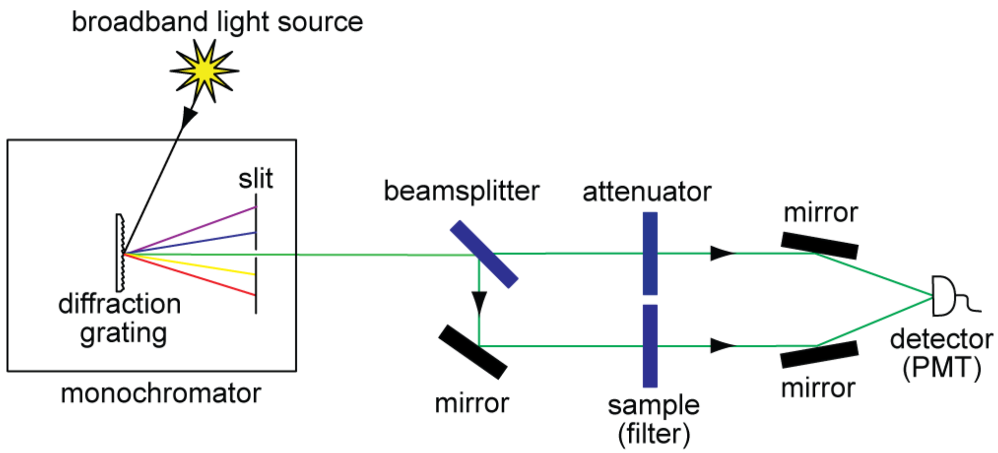

Figure 1: Simplified diagram showing the main elements of a dual-beam spectrophotometer.

In an actual spectrophotometer, there is a more complex system of optics and electronics required to avoid measurement errors introduced due to alignment issues, imperfect components, scattered light, and other optical and electronic noise sources. Despite the availability of such advanced instrumentation, critical features of high-performance optical filters with steep edges and/or deep blocking can not be accurately measured by these spectrophotometers.

3. Limitations of the conventional measurement approach

Conventional spectrophotometers have limited sensitivity and the probe beam is not perfectly monochromatic. As a result of these limitations, three main discrepancies appear between an actual filter spectrum and its measured representation. The first discrepancy is the "rounding" of sharp spectral features (see Fig. 2). This effect results from the non-zero bandwidth of the spectrophotometer probe beam. The minimum bandwidth is limited by the slit width and the number of grating periods the light sees – the larger the area of the diffraction grating (for a given number of lines per mm), the higher the resolution. For a given f/# (cone angle) a larger grating area also requires a longer path length and therefore a larger instrument. Resolution can also be increased by reducing the slit width, but a narrower slit reduces the amount of light passing through the monochromator to the detector, and therefore reduces the sensitivity.

The second measurement discrepancy arises from limited sensitivity of the spectrophotometer. When a filter has high OD (such as OD > 6), very little light reaches the detector, and optical and electronic noise at the detector limit the lowest signal that can be measured accurately. The signature of this artifact is a flat, noisy spectrum that appears to be "pinned" to a certain OD value, despite the fact that the actual filter OD can be substantially higher than the represented value. This signal limit is often called the "noise floor," and it can be wavelength dependent due to variations in the light source and detector response spectra. Note that the noise floor can be decreased allowing for higher OD measurements by opening up the monochromator slits and letting more light through the system, but this increased sensitivity must be traded off against poorer spectral resolution.

The third discrepancy is unique to measurements of very steep transitions from high blocking to high transmission, and is referred to as a "sideband measurement artifact" (see Fig. 3). It often takes the form of a "kink" in the edge spectrum when plotted in OD units, usually occurring in the range of about OD 2.5 to 4.5, depending on the spectrophotometer and wavelength. This artifact arises from the non-monochromatic probe beam – in addition to the non-zero bandwidth of the probe beam, it also has weak sidebands at wavelengths outside of its bandwidth that arise principally from imperfections in the grating. When the probe beam is located at a wavelength on a very steep edge, instead of being attenuated at the OD level of the filter, sideband noise on one side of the probe wavelength is transmitted by the filter within its passband, thus registering a larger signal on the detector and leading to a lower OD reading

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than is actually present. In a commercial instrument, there is little one can do to reduce this sideband artifact, except to add additional filtering (see Section 4 below).

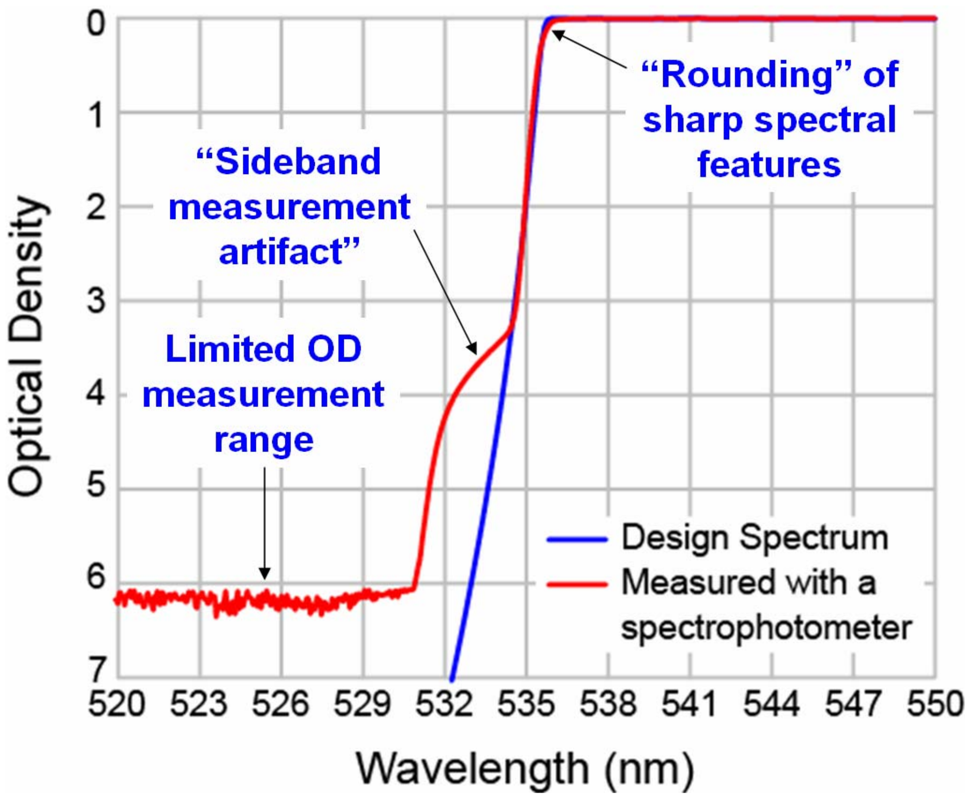

Figure 2: Example showing design and measured spectra of a Semrock LP03-532RU-25 RazorEdge® filter. Measurement was made using a commercial spectrophotometer.

These measurement discrepancies in conventional spectrophotometers cause significant problems when trying to assess the performance of the filter for its intended application. For example, the filter shown in Figure 2 is used primarily as a "Rayleigh filter" for Raman spectroscopy applications – it's purpose is to provide OD > 6 blocking of a 532.0 nm laser line while transmitting the Stokes-shifted Raman signal very close to the laser line. But because of the measurement discrepancies (in this case primarily the sideband artifact), it is not possible to immediately determine whether the filter achieves OD > 6 at 532.0 nm just by looking at the plot. Nevertheless, by fully understanding and characterizing the spectrophotometer limitations it is possible to at least approximately infer the actual filter performance. For example, since it can be shown that no reasonable perturbation of the thin-film layer structure from the exact, designed structure could give rise to the sideband artifact spectral signature, the edge spectrum can be determined approximately at OD values higher than the "kink" value by extrapolating the curve from lower OD values and using the design curve as a limiting guide. However, the spectrophotometer optical system can also be improved so that inherently better measurements are possible, either through enhancements to a commercial instruments or by development of fully customized spectrophotometers. Semrock utilizes all of these approaches to make the most accurate spectral measurements that are needed for a given filter or application.

4. Enhanced measurement techniques for steep and deep edges

Semrock utilizes different measurement approaches to evaluate different filters at different stages during the manufacturing cycle to varying degrees of accuracy. As an example, Figure 3 shows five measured spectra of the steep edge of an "E-grade" RazorEdge filter that is guaranteed to block a laser line at 532 nm with OD > 6 and transition to high transmission within 0.5% of the laser wavelength (by 534.7 nm). The measured spectra are overlaid on the design spectrum of the filter (blue line). As observed in this figure, choice of a particular measurement instrument and technique greatly influences the measured spectrum of a filter. Major differences between the techniques are highlighted below.

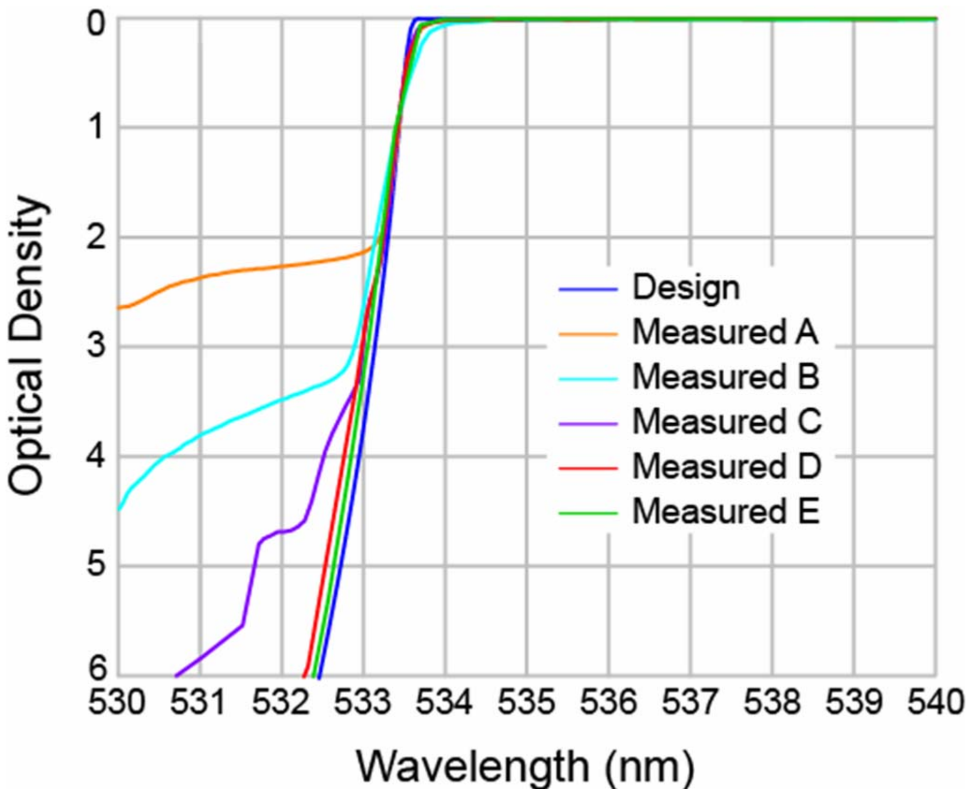

Figure 3: Example showing design and measured spectra of a Semrock LP03-532RE-25 RazorEdge® filter. Measurements were made using both commercial and custom-made spectrophotometers with a variety of different settings as explained in the text.

Measurement method "A" in Figure 3 is made by a custom-built spectrophotometer (described in more detail below). This measurement uses instrument settings – such as short detector integration time and low resolution – that are optimized for very rapid data collection from a large number of sample filters. It is used primarily for locating the edge position so that the spectral uniformity of a complete sample of filters from a thin-film coating run can be accurately tabulated. It is an important part of the thin-film filter manufacturing process to make on-going uniformity adjustments to the deposition machines and for quality assurance. While the technique is very fast, the compromise that results from the choice of instrument settings is poor sensitivity and resolution, as can be seen on the plot – the noise floor is barely above OD 2.

Measurement method "B" uses a standard commercial spectrophotometer (Perkin Elmer Lambda 900 series), the basic operating principles of which are described in Section 2. It is essentially identical to the measurement used to generate the spectral plot in Figure 2. Thus, all of the discrepancies between the actual filter spectrum and the measured spectrum described in Section 3 are apparent: limited resolution leading to rounding of sharp features, limited sensitivity leading to an OD noise floor (not visible on this plot since the floor is only apparent at wavelengths shorter than the plot extent), and the "sideband artifact" that causes the "kink" in the curve around OD 3.5 and a sudden apparent decrease in steepness of the edge. Note that the filter shown in Fig. 3 is about two times steeper than the filter displayed in Fig. 2, and therefore these discrepancies in Fig. 3 appear more pronounced than in Fig. 2. As in the example in Section 3, note that again the limitations cause significant problems when trying to assess the performance of the filter for its intended application – it is not immediately apparent using this measurement method that the filter achieves blocking of OD > 6 at 532.0 nm.

Measurement methods "C" and "D" utilize the same custom-built spectrophotometer from method "A." The basic principle of operation of this spectrophotometer is shown in Figure 4. The primary difference between this instrument and a standard commercial spectrophotometer is that detection in the custom-built system is done with a low-noise CMOS camera (i.e., detector array) capable of measuring a wide range of wavelengths simultaneously, rather than measuring each wavelength data point sequentially as the grating angle is scanned. The main advantage of this approach is that it is much faster – a broad spectral measurement at a given resolution and with a given integration time (and resulting noise floor) can be made much more rapidly. One might ask why all spectrophotometers don't utilize this principle since it offers significant speed advantages. Note that the approach of the custom-built spectrophotometer requires the test sample to be illuminated with broadband light, so that a broad range of wavelengths can be captured simultaneously by the detector array. Illumination with broadband light does not pose any significant problems when the test sample is a glass optical filter, but could pose problems if the sample exhibited appreciable autofluorescence, for example, which could interfere with an accurate measurement of only the transmission through such a sample. Because commercial spectrophotometers are designed to work with a wide range of possible test samples, including those that are very sensitive to broadband illumination or exhibit autofluorescence, it is preferable to probe the sample with quasi-monochromatic light in these instruments. The custom-built spectrophotometer does use some additional filtering of the light source prior to the test filter (see filter wheel in Figure 4) to eliminate unnecessary stray light and higher-order diffracted light from the grating downstream. The light transmitted through the test filter is transmitted through a double monochromator with a cooled, UV-enhanced CMOS camera to collect the light.

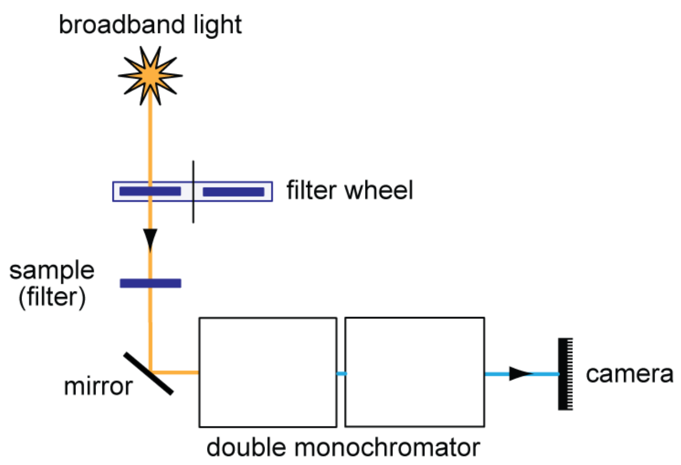

Figure 4: Basic layout of a custom-built spectrophotometer based on broadband illumination of the test filter and collection of a broad range of wavelengths simultaneously with a detector array. This approach enables faster measurement with a given noise floor and resolution.

Measurement method "C" uses instrument settings (primarily integration time and resolution) designed to provide accurate measurement of the steep and deep edge, including the sharp "corner" at 533.5 nm. The measurement is comparable to or better than what is possible with a commercial spectrophotometer (method "B"), and can be made in less time. However, notice that the "sideband measurement artifact" is still apparent, as manifested in a sudden "kink," or decrease in apparent edge steepness, at about OD 4.5. The sideband artifact problem can be mostly eliminated by applying additional filtering of the light at wavelengths within the passband of the sample filter before and/or after the sample filter, thus preventing this light from being diffracted by grating imperfections into pixels that correlate to wavelengths that are highly blocked by the filter. Measurement method "D" is a modification of method "C" that applies this additional filtering. As can be seen in Figure 3 by comparing measurement "D" to the blue design curve, the sideband artifact is mostly eliminated, though there is still a very slight "kink" in the edge that starts at about OD 2.5. The discrepancy remains very small – less than 1 OD – even at very high OD values, though.

To even further eliminate the sideband artifact, measurement method "E" shows the results of a very precise measurement made with a carefully filtered 532 nm laser and angle tuning of the filter itself. The laser is a diode-pumped solid-state frequency-doubled Nd:YAG laser. A narrowband filter is used to eliminate any laser noise immediately adjacent to the 532 nm laser line, and broadband filtering is used to eliminate non-neighboring light emitted from the laser, such as the fundamental 1064 nm output. A tunable filter and low-noise detector are also employed (built into an ANDO AQ6315A optical spectrum analyzer). Data for this measurement was taken over a range of angles-of-incidence of the laser light on the filter, and then the data was subsequently converted from transmission vs. angle to transmission vs. wavelength using a theoretical model based on the thin-film coating structure. Clearly, this measurement method comes closest to the actual design curve, and we believe it is the most accurate method for measuring a filter with a very steep and deep edge. However, disadvantages of this method include the need to have a precise, highly monochromatic laser at the filter edge wavelength to be measured, and the fact that at least at present it is a careful, time-consuming measurement performed by an engineer in an optics lab, rather than a robust, production-environment method suitable for quality assurance of large volumes of filters.

5. Measurement of very high OD

For some filters and applications the edge steepness is not so high nor critical to the performance, yet the blocking level at a particular wavelength or over a range of wavelengths is critical. For example, in a fluorescence imaging system the absorption and emission spectra of the fluorophore might be sufficiently far apart that the throughput is not limited by the proximity of the exciter and emitter bandpass filters, but it is nevertheless critical that the exciter achieves very high blocking over the emitter band and/or vice versa to achieve a suitable signal-to-noise ratio. Such filters can be designed to have dozens of OD of blocking, but in practice even the tiniest of physical defects in the optical coatings or mounting, as well as imperfections in the control of system-level stray light, limit the achievable blocking to values in the range of about OD 6 to maybe 10. Given that standard spectrophotometers have a limited OD measurement range due to the instrument noise floor explained in Section 3, how can higher blocking levels be accurately determined?

A straightforward, production-compatible technique for assuring higher OD values (up to OD 8 or even 9) is called the "complementary filter method." The basic principles of this method are illustrated in Figure 5. An approximately collimated broadband beam of light from a QTH or arc lamp is filtered using a widely blocking *reference filter,* which is essentially a bandpass filter with its passband overlapping the region of spectrum of the *test filter* where high OD measurement is required. The transmitted light is focused onto a low-noise detector capable of measuring very small light levels, such as a large-area photodiode with a low-noise amplifier circuit or a photomultiplier tube (PMT).

The measurement proceeds as follows. First, the signal strength on the detector is recorded with only the reference filter and a calibrated neutral-density (ND) filter in the light path. A typical ND filter choice is about 3. The purpose of the ND filter is to reduce the light level on the detector by a calibrated amount so that the limited dynamic range achievable by practical detectors can be biased down to reach the signal level that will be seen by the detector when the test filter has OD 8 or 9 blocking. In other words, with an ND 3 filter, the detector dynamic range needs to be only 10^6 to measure up to OD 9 blocking. In the next step of the measurement, the ND filter is removed from the light path and replaced by the test filter. The ratio of these two measurements gives the OD of the test filter over the spectral range of the reference filter (after removing the calibrated ND value). To achieve OD levels as high as 8 or 9 and ensure accuracy of measurement, it is vital that the measurement setup be sufficiently shielded from ambient light and minimize scattered or other stray light from reaching the detector.

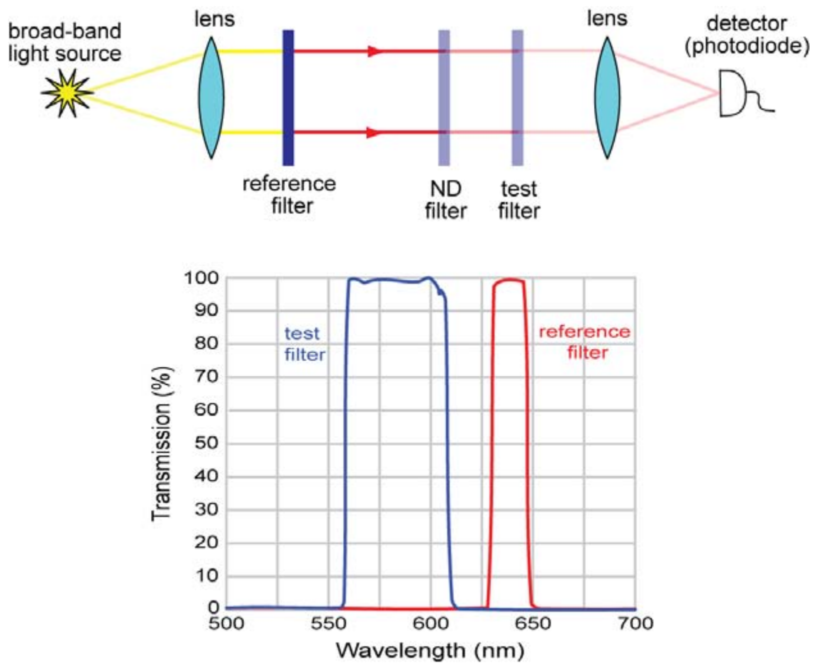

Figure 5: Measurement of very high OD values. The reference filter covers the range of wavelengths over which high OD must be verified in the test filter.

One might think that measurement of the OD level over different blocking regions of the test filter requires different reference filters and multiple measurements. However, note that physical defects which reduce the OD from the designed value do so at every wavelength where a given coating blocks light. Thus, if it can be shown that there are no defects that reduce the blocking to below, say, OD 8 in one wavelength region, then the blocking will similarly not be reduced to below this value at other wavelengths blocked by that same coating. As a result, generally only one reference filter and measurement are required for each test filter.

In summary, it is important to understand the measurement techniques used to generate optical filter spectra, as these techniques are not perfect. Use of the appropriate measurement approach for a given filter or application can reduce errors as well as over-design of experiments and systems that use filters, thus optimizing performance, results, and even filter cost.

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