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Characterizing the Performance of Optical Interference Filters with Deliberate Large Variation in Spectral Response. ***Some thoughts on the measurement of linear variable filters…***

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Abstract

From time to time people are interested in optical filters whose response changes with position. Frequently the desire is for a filter that changes in one direction and remains constant in the perpendicular direction. The deliberate nonuniformity and anisotropy of these filters adds significant complications in the characterization of their spectral performance.

In the spectral measurement of real devices the size of area illuminated on the filter produces a measurement of the beam irradiance weighted average performance. In most commercial spectrophotometers this is an image of the entrance slit of the monochrometer and is typically around 2x7 mm. For optical interference filters, changes in the thickness and refractive index across the part result in changes in the spectral performance or in the uniformity. Among other things, the ability to control the uniformity determines the size of a filter that can be manufactured to a given tolerance. The narrower the filter, the tighter the control must be to fabricate a filter of the same size.

Introduction

In Linear Variable Filters (LVF) our goal is to still control the thickness and index variation, but instead of targeting a constant value, we are after one that changes in a predetermined, usually linear, manner. We call this target the "filter dispersion" (FD) in order to offer the greatest likelihood of confusion with the material dispersion (MD) with which it is intrinsically linked. MD is the change in refractive index as a function of Wavelength. The FD of a LVF is the change in the filters central wavelength with position. In the visible region of the optical spectrum both the real and imaginary parts of the refractive index increase toward shorter wavelengths. MD is a materials-dependent parameter so that each material in a given design will have its own change in index with wavelength. FD is determined by the change in optical thickness of the filters constituent layers. The way Materion creates LVF, the relative thickness of the layers is fixed by the design and the total thickness changes as a function of position. In this manner, any filter type could be a LVF.

There are two types of LVF that dominate the market - Long wave pass (LWP) and Band pass (BP). A typical use of a LWP LVF is for order suppression in grating-based spectrophotometers. For these filters, the spectral response of interest is the transmission at two wavelengths that are widely separated, i.e. the measured wavelength λ and spurious signals from other grating orders that are spatially coincident, $\lambda/2$, $\lambda/3$ etc. A BP LVF, if used in conjunction with a pixilated detector, becomes a spectrometer on a chip. As an example of LVF BP, consider a narrow band filter with a 1% bandwidth designed to operate over the Visible and NIR wavelength range of 400 to 900 nm for use with a CCD Array that is 25 mm long. The FD of this filter is 500 nm/25mm or 20 nm/mm.

In **Figure 1**, the modeled spectral response is shown at three locations spanning the length of the filter. This calculation shows some of the aspects of LVF BP filters as we create them. In particular, the bandwidth of the filters is not constant and the filters' width is proportional to its wavelength. This proportionality is not exact, however, because the two materials have unique MD. The difference in MD causes the refractive index contrast and hence the cavity finesses to decrease with wavelength. This results in an increase in the filter bandwidth.

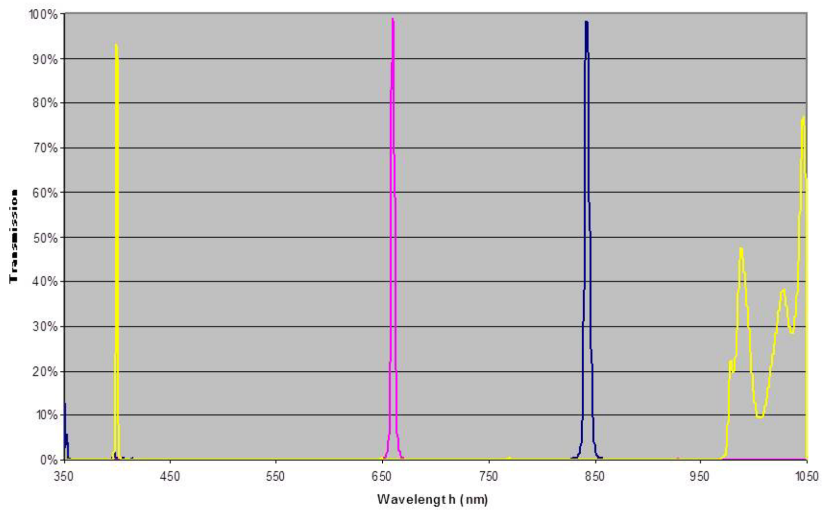

Figure 1. Calculated spectral response for three positions of the filter 0,13, and 22 mm for a spectrometer with an infinitely small sample area, a 0.25 nm spectral bandwidth and an f/50 beam.

When we measure a filter like this one in our standard spectrophotometers, we frequently obtain disappointing results. In **Figure 2** and **Figure 3** the measured spectral performance of a BP LVF with different FD are shown.

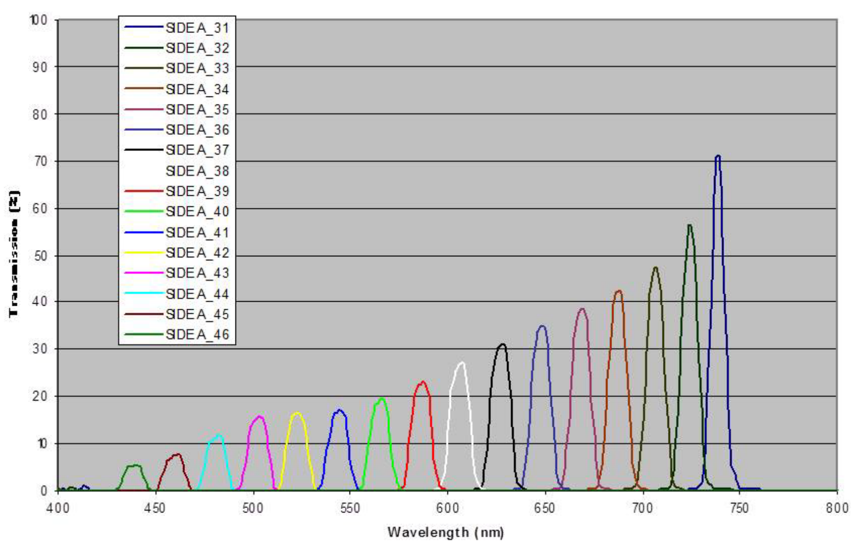

Figure 2. Moderate slope The peak transmission in Figure 2 decreases and the shape degrades rapidly as we move from longer to shorter wavelengths.

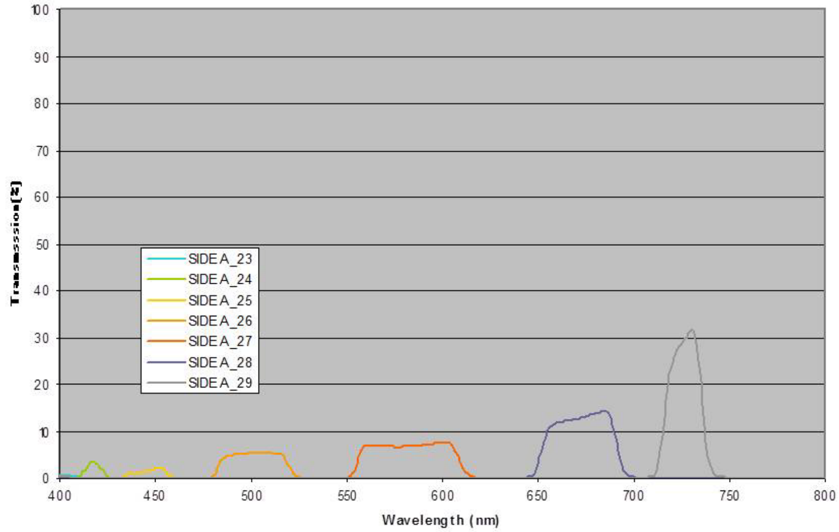

Figure 3. Large Slope

These two measurements are disappointing in a number of respects. The peak transmission of the filters is low, the shape bad, and both change dramatically with position. Instead of becoming broader as the wavelength increases, the width of these measurements is nearly constant.

These filters were produced simultaneously and hence they should have nearly identical layers, whether good or bad, they should be the same.

How to we explain the differences? What can we do to improve the measurement so that we can determine the “real” performance of our filters?

In order to determine the sources of these discrepancies, we have developed hardware and software tools to address the issue. The software simulates the performance of our filters using standard thin film calculations based on the matrix method. The code can simulate the effects of fabrication, spectral bandwidth, cone of illumination and area of illumination.

In our spectrophotometer, we use a secondary slit aperture located next to the sample to define the area of interrogation. As all of the spectrophotometer parameters were constant for the two samples, and they were deposited simultaneously, the difference in these two spectral outputs must be a result of difference in slope.

The most likely sources that can contribute to the bandwidth issue are spectral bandwidth and spatial averaging of the nonuniformity of the filters. For a fixed integration area of the filters, the filters center wavelength will change by the FD X slit width. In this case, the measurement slit is about 0.7 mm. A filter with 20 nm/mm dispersion would change center wavelength by 14 nm within the aperture; a filter with 100 nm/mm FD, **Figure 3**, would change by 70 nm.

Simulation of the effect on central wavelength span on measured performance is shown in **Figure 4**. From this graph we see that as the spatial averaging smears the filter out, it increases the apparent bandwidth and decreases the Transmission. To eliminate this effect, one needs to maintain the area*FD below about one half of the bandwidth.

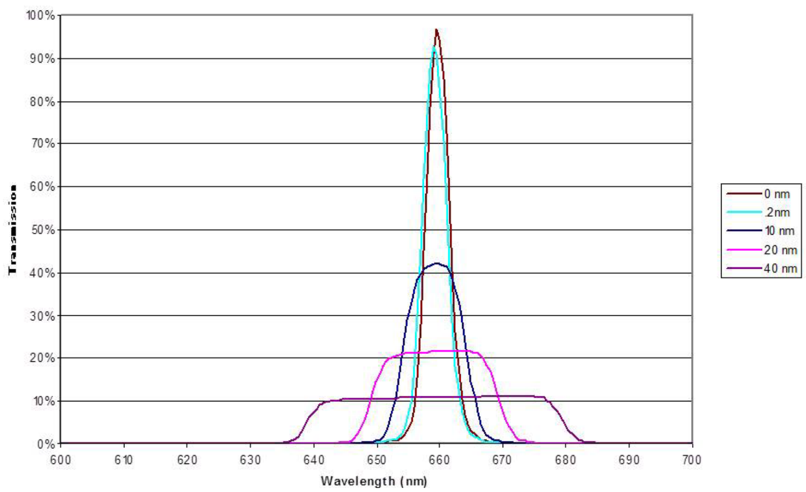

Figure 4. Simulation showing the effect of increasing the center wavelength shift over the aperture for a 5 nm wide filter at 660 nm.

Instead of varying the area of integration for each FD, we have constructed a bench top instrument that gives us the highest spatial resolution on the filter and allows us to map the filters performance as illustrated in **Figure 5**.

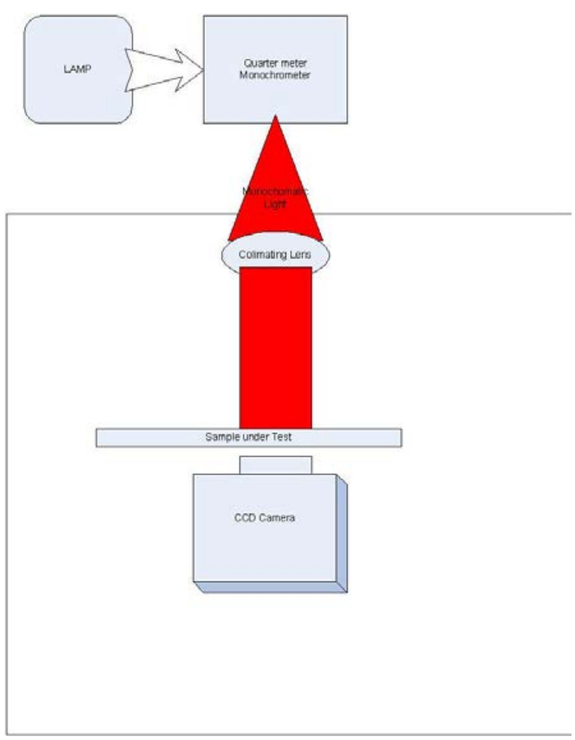

Figure 5. Schematic of our test method.

In this method we use a standard one quarter meter monochrometer to provide monochromatic illumination. The output of this monochrometer is allowed to expand and then be collimated. This beam then illuminates the LVF at near normal incidence. A CCD array is then placed as close as possible to the filter. Ideally, the CCD array would be placed in direct contact with the filter thus defining the area of integration by the pixel size, in our case 9 µm. The lack of any optics behind the filter makes it a simple and direct method of mapping the performance of the filter. By scanning the monochrometer, we can then measure the spectral response of the device. A single frame of output of an unblocked bandpass filter is shown below in **Figure 6**.

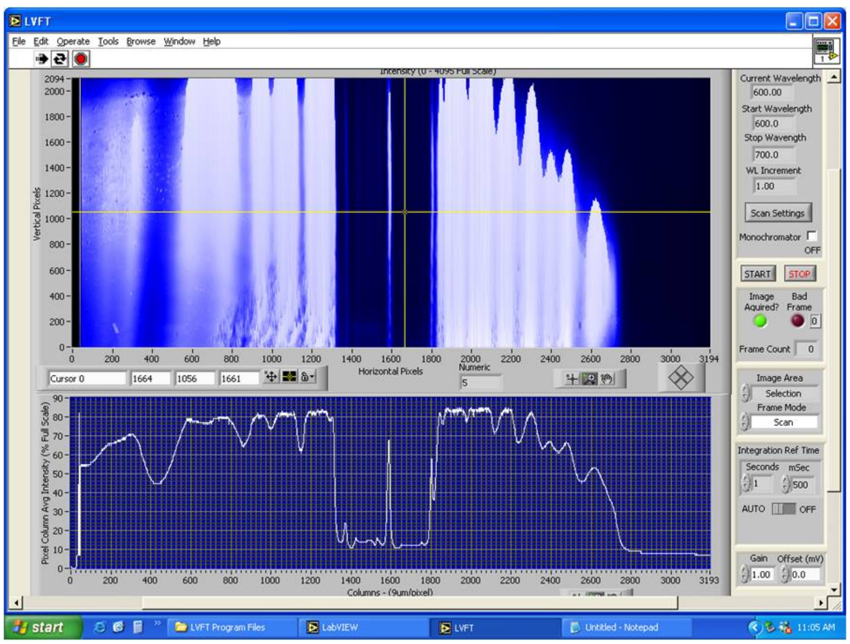

Figure 6. Screen capture of an unblocked LVBP Filter measurement at 600 nm showing entire collection area approximately 1” high by 1.25” long. In this filter the FD is in the X direction.

We record the data by adding the measured values column by column, illustrated in the figure as the graph at the base. This data is stored producing a data file of 3200 entrees.

It is worth observing that the illustrated filter shows very little deviation from straightness in the direction perpendicular to change, i.e. very little smile.

To account for illumination and noise variation, we take three sets of data: the sample, a background and a dark. As the response of the system can vary widely over the range of wavelengths, we adjust the integration time to compensate. These files are combined to produce a transmission spectrum of the device at each pixel column.

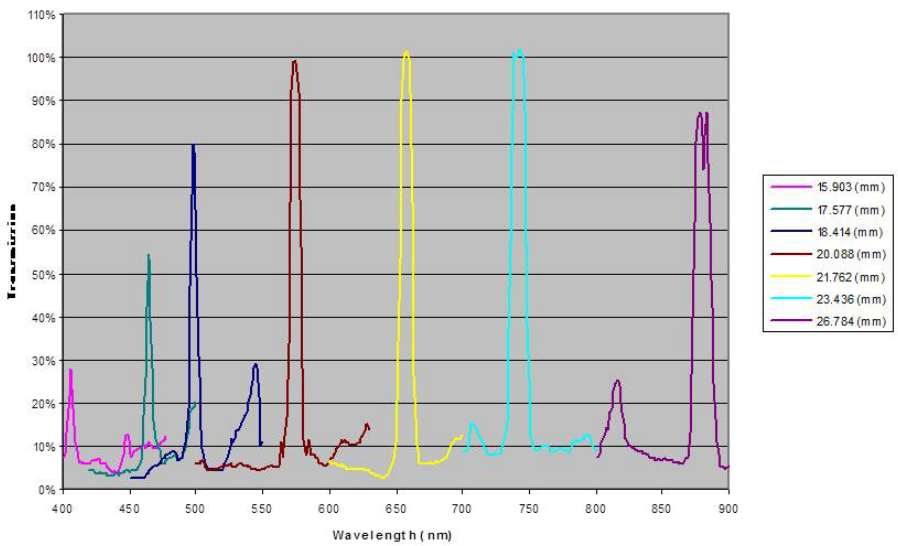

Figure 7. Measured Spectral response at several locations along a LVBP filter.

From this data, we can readily extract the FD curve - in this case a filter with 44.8 nm/mm spanning the visible and NIR in about 10 mms.

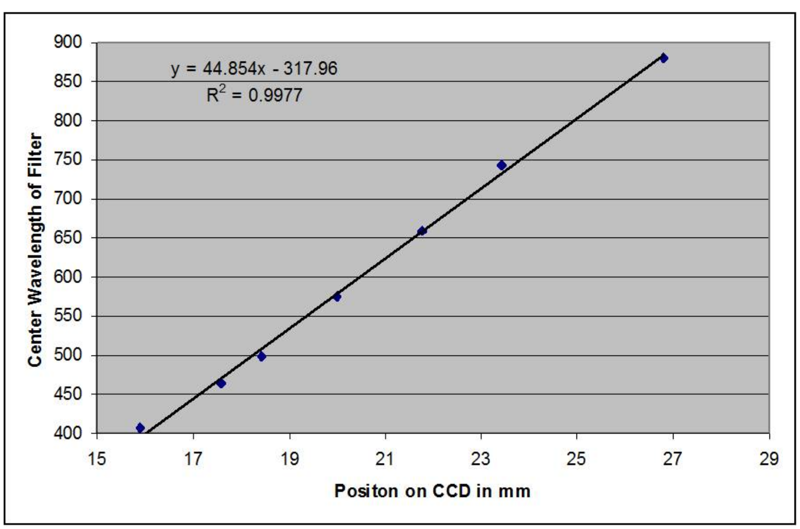

Figure 8. Calculation of the Dispersion in the filter shown above.

This instrument is a work in progress. We have progressed as to where it is useful for deposition diagnostics and performance evaluation. However, the length of time required to make a measurement is quite long (several hours). The dynamic range is limited. The CCD is not in intimate contact with the filter and so there are some spurious signals resulting from light being reflected off the CCD. This impinges on the filter in a high reflection zone and then back onto a different area of the detector with the resulting appearance of a leak. The spectral band of the monochrometer is sufficient for the filters we have produced thus far. Translating the filter and stitching the images together can accommodate filters with larger extent. The minimum filter extent (i.e. the measured bandwidth) is an average along the CCD columns. Thus, any angular deviation of the filter axis and the measurement axis will result in broadening the filter response function much in the same manner as filter nonuniformity.

In conclusion, LVF filters can be measured using our in-house built imaging spectrometer for filters in the visible and NIR. The technique is extendable to other wavelength régimes for which pixilated detectors are available. The small area of the individual pixels allows us to measure narrow filters with high filter dispersions, perhaps even to filters where our standard calculation methods no longer accurately predict the performance.

Visit Materion Precision Optics to learn more about our linear variable filters and other optical interference filters.

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