Measurement and alignment of linear variable filters

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ABSTRACT

Linear variable filters have become a common way to impart wavelength selectivity into optical systems with a minimum of optical elements. Long-pass, short-pass and band-pass filters of various spectral widths and different spectral –spatial gradients across the part have been employed and can be manufactured in a relatively straightforward manner with proper mask design. Most manufacturing methods impart a slight curvature to the gradients because of rotation of the parts across the targets during the deposition process. Measuring the filter in the presence of steep spectral-spatial gradients is the primary difficulty in characterizing these filters, requiring a small aperture beam resulting in a corresponding loss of signal power. We will discuss our approach to mapping the spectral and spatial distribution of these parts as well as a method to specify these filters. We will also suggest methods to calibrate and align the filters onto a detector, camera or chip.

Keywords- linear variable filter, continuously variable filter, wavelength mapping, spectroscopy, characterization, calibration, hyperspectral imaging

1. INTRODUCTION

Linear variable filters (LVFs) have become a very popular tool for performing relatively inexpensive wavelength selection and/or order-sorting using a single optical element without moving parts. These filters combine spectral and spatial properties on a single piece of glass. These filters are used in a myriad of applications from hyperspectral imaging of agricultural fields,[7] to flow cytometry, to chemical sensing.[6] Typically a spectral gradient follows only one axis of the part while the other direction is constant, creating a "rainbow" effect across the part (Figure 1). Given the large number of applications, there are an equally large number of optical layouts which use them. Often (but not

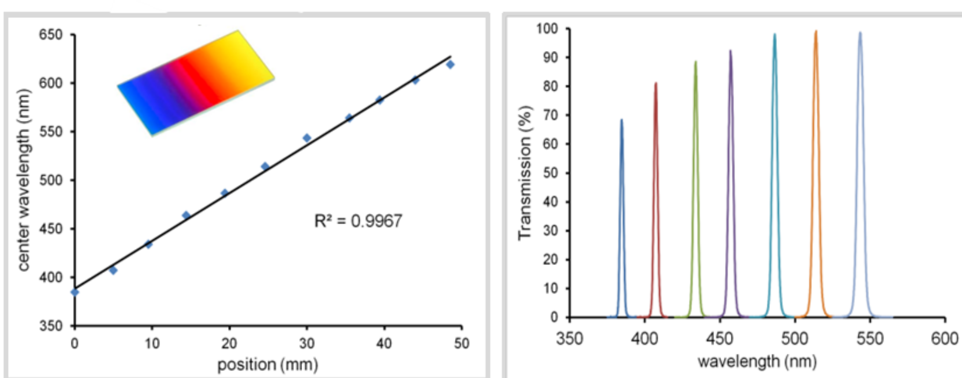

Figure 1. Bandpass linear variable filter. Left- center wavelength versus linear position and photo of the filter, Right- individual spectral traces at sequential points along the gradient.

always), the LVF lies close to the focal plane of the detector chip or array, using a beam geometry that ranges from collimated (f/inf) to f/1. Most customers are interested in how filters will perform in their given application using their own optical design, and not how the filter performs in standard production testing. Herein, we will illustrate the caveats in measuring and designing optical systems that contain these filters. Throughout this paper "gradient" refers to the spatial distribution of the spectral curves across the part. These can be short-pass (SP), long-pass (LP) or band-pass (BP) designs where the spectral features of interest increase or decrease in wavelength across the part.

When ordering a LVF, a number of parameters must be specified by the customer including the desired spectral shape (BP, LP, SP) and edge slope, the spectral range and deepness of blocking and the spectral-spatial gradient across the part. Like all interference filters, the design of the filter stack is influenced by the angle-of-incidence (AOI) and ½ cone-angle (NA or f/#) of the incoming light. For the steepest spectral edge slope (cuton and cutoff), collimated light is required as explained below. In this paper "slope" refers to the rising or falling edge of a BP, SP or LP filter with respect to wavelength at a single physical position on the part.

2. MEASURING LINEAR VARIABLE FILTERS

Measurements of LVFs are complicated by competing objectives. First is the production environment and process control. For this task, measurements of the spectral/spatial gradient distribution are used to refine the production process and ensure the method is robust. Typically, for this application, Omega uses a small, collimated beam which can show variability across the part perpendicular to the gradient, as well as parallel to the gradient. The second objective is customer-driven and involves characterizing the spectral properties (such as edge steepness and center wavelength), the functional performance and alignment of the filter in the customer's optical system.

Sec. 2.1 Characterizing the gradient

A small, collimated beam enables the most accurate results for whole-part mapping for process control. Interference filters are strongly affected by AOI, so a collimated beam is necessary.[1,4] When the AOI is not normal to the surface, the salient spectral features shift to lower wavelengths, which can make the filter appear to be out of specification.[1,3,4] Further, if the part is measured in a system with a converging beam, the resulting spectrum will be a convolution of all the angles contained within that ½ cone angle (Figure 4). This causes an effective reduction in %T (for BP filters), a reduction in slope (for BP/LP/SP filters) and a shifting to lower wavelengths of the center wavelength (BP filters) or edge (LP/SP filters).[1,3,4]

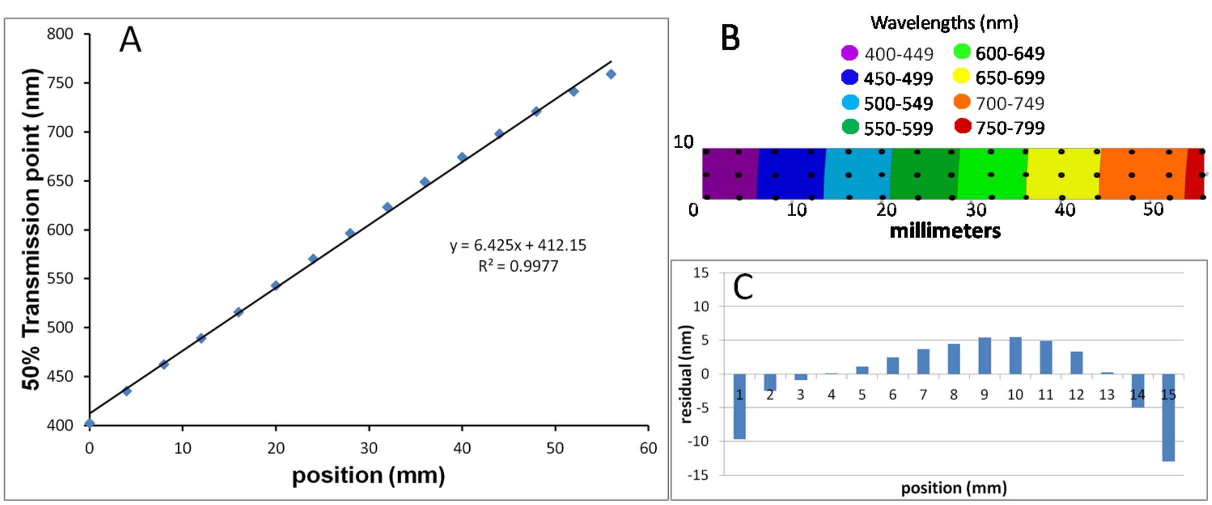

Figure 2. Measurements and map from a LP-LVF produced using a mask and rotating platen. A. Spectral-spatial gradient curve from the 5 mm position, B. Color-coded map of the wavelength at 50% T of the LP with measurement positions marked with dots, C. Residuals from the line fit in panel A.

Figure 2 shows measurements from a long-pass LVF manufactured using a standard method that generates a small amount of curvature in the direction perpendicular to the spectral/ spatial gradient. It was measured using a 200 µm diameter spot size with a ½ cone angle of 3.58° (f/8). Measurement points are illustrated with small circles in Figure 2B and the 50% T wavelength was extrapolated between points to generate the map. The slight curvature in the wavelengths in the vertical direction is barely visible in this example. Figure 2A shows a spectral-spatial gradient of about 6.4 nm/mm in the middle of the part and Figure 2C shows the residuals from the line fit. Residuals are deviations of the measurement from the line fit. Even with a very good line fit ($R^2 > 0.99$), residuals over 10 nm are common. For a relatively small gradient like this, the wavelength changes by about 1.3 nm within the 200 µm spot diameter.

The above example hints at several of the measurement difficulties that become problematic as the spectral-spatial gradient increases. Measurement errors are compounded by an uncollimated beam, spatial inhomogeneities and a spot size that samples a number of wavelengths simultaneously due to the nature of the spatial-spectral gradient itself. Collimating the beam and reducing the spot size allows us to more accurately measure steeper spectral-spatial gradients as seen in Figure 3 which achieves a spectral-spatial gradient over 50 nm/mm with a relatively flat spatial profile across the 25 mm part. This early prototype was measured with a 50 µm spot size and 0.26° ½ cone-angle (f/100). Given the very high spectral-spatial slope, the 50 µm spot still samples about 2.6 nm of wavelength change.

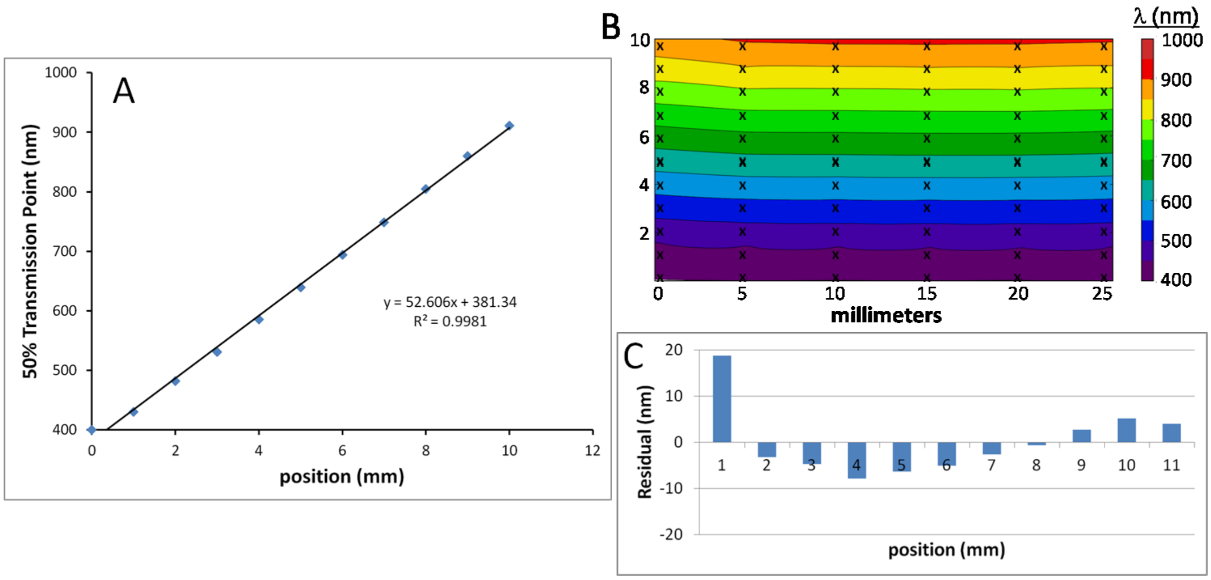

Figure 3. High spectral-spatial slope, high-pass LVF under development by Omega Optical. A. Spectral-spatial curve from the 15 mm position, B. Color-coded map of 50% T versus position with measurement positions marked with x, C. Residuals of the line fit from panel A.

Sec. 2.2 Characterizing the spectral and functional performance

The spectral/spatial maps above are a summary of a single spectral feature (center wavelength, cuton wavelength, etc.) as a function of position on the part. Most customers also specify performance parameters such as edge steepness, blocking depth and range and functional performance that depend on many of the parameters mentioned above including:

1. Cone angle and AOI – both reduce the slope between transmitting and reflecting (blocked) regions[1] and the effective transition wavelength (Cuton, cutoff or center wavelength). If the customers specify use in a collimated beam, the ½ cone angle may be zero while the AOI may be at a fixed angle. Customers with imaging applications may have

an AOI of zero with a very large ½ cone angle (in the case of a short focal-length lens in front of the detector for example). The effect of increasing the ½ cone angle (decreasing the f/#) on a single LP filter is illustrated below in Figure 4. The wavelength at 50% T decreases as well as the slope of the blocking to transmitting region (cuton). Similarly for a BP design, the center wavelength shifts to a lower value, the full-width half-max increases and the slope of the two sides of the band become less steep and the peak %T is reduced.[1]

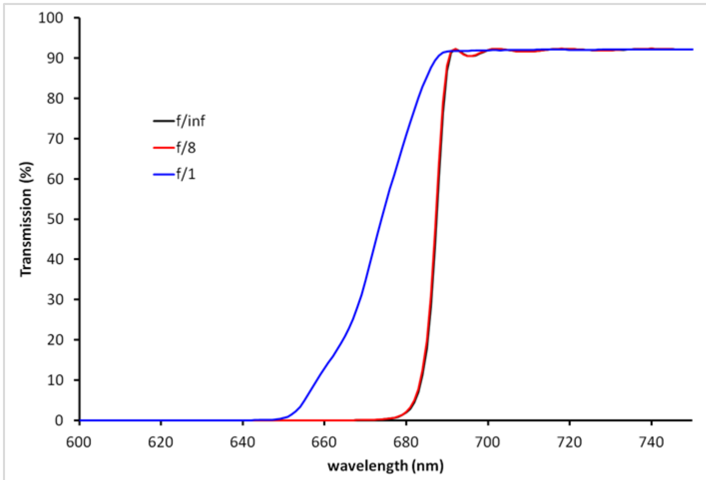

Figure 4. Model curves of %T versus wavelength for a single LP filter with AOI=0 and different cone angles (f/#). The increase in cone angle causes a decrease in the slope of the cuton wavelength.

2. Spot size – many wavelengths are sampled at once because of the spectral-spatial gradient itself. There is a trade-off between spectral resolution (which requires a very small spot size) and signal-to-noise (which requires a larger aperture). This can be partially overcome by using a slit aperture with the long axis perpendicular to the spectral-spatial gradient in an attempt to sample a single wavelength band. Of course, inhomogeneities in this direction will alter the measurement as well. Figure 5 demonstrates the effect of slit size and shape on the spectral measurement.

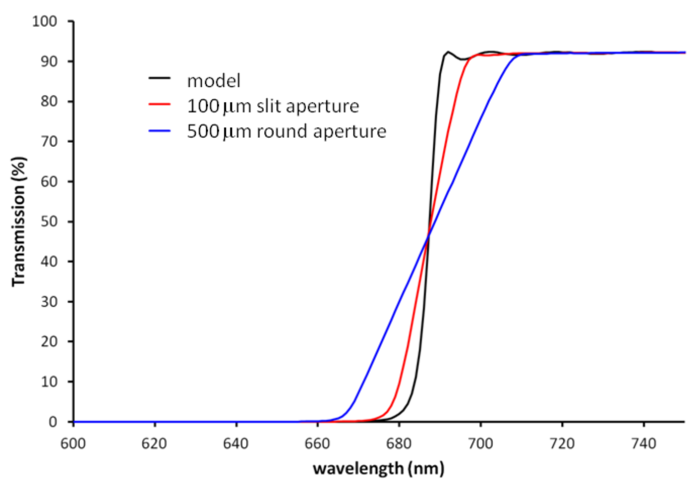

Figure 5- Modeled spectra using different aperature sizes and shapes in an f/8 beam. The slit aperture is aligned perpendicular to the spectral- spatial gradient. The gradient in this sample was ~75 nm/mm.

The narrower slit helps maintain a high signal-to-noise ratio while providing more detail about the spectral shape of the coatings. In this example, the slit samples roughly 7.5 nm of spectral gradient and the circular aperture samples about 38 nm, which smears out both the edge slope and other spectral details such as ripple. Because the aperture is centered around the same middle position, the curves all share the same 50% T wavelength, but the effective slope of the curve is reduced by a greater spot size.

3. Distance from the part to the detector- ghost images can be introduced if the light reflects off the surfaces of the filter and detector, especially if they are in close proximity. There are several methods to minimize this effect including anti-reflecting the uncoated side of the filter and coating directly on the sensor chip. Of course, depositing directly on the sensor will not address AOI issues or signal-to-noise problems from scattering within the thin-film itself.[2]

3. CALIBRATION AND ALIGNMENT OF LINEAR VARIABLE FILTERS

Rather than having the manufacturer exquisitely map the wavelength positions of the filter, another option is for the customer to map and correct the data with software calibrations. During assembly, one can position the filter on the sensor using an expanded laser(s) to align the filter to the sensor based on the position of the wavelength transmitting the filter (Figure 6). A series of lasers can be mapped to pixel position to create a calibration curve for the system. A similar process can be used for SP or LP LVFs, where the cuton or cutoff wavelength of each laser is plotted to a calibration curve. Multiline gas light sources can also be used to align the filter to the detector chip.[6]

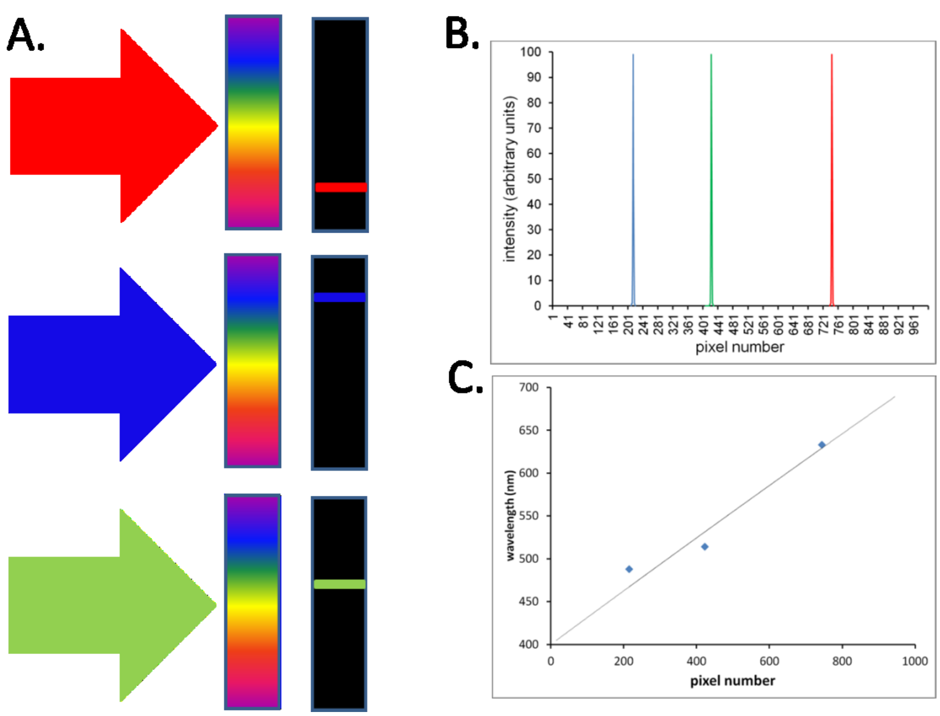

Figure 6. A. In the case of a BP LVF, expanded laser lines can be used to align the filter (multicolored rectangle) to the detector (black rectangle), shown graphically in B. C. A plot of pixel number versus laser wavelength is used to generate a calibration curve for the filter/ detector assembly. If the filter exhibits significant smile, a similar curve can be generated for each row of pixels in a 2-D detector and the signals can be combined in software.

4. CONCLUSIONS

The characterization of linear variable filters is complicated by the way they are manufactured and the properties of interference filters including angle of incidence, ½ cone angle, spatial non-uniformities in the spatial-spectral gradient and the nature of the spatial-spectral gradient itself. Some of these variables (such as AOI) can be optimized at the design phase, but close communication between the customer and manufacturer is required to achieve the expected results. By recognizing and optimizing these variables, accurate maps of the spatial-spectral response of the filters can be made. Customers can use lasers or multiline light sources to help position the filters in their assemblies and create calibration curves for use in their software systems. As these filters become more popular in optical designs, a standard specification scheme should be developed based on desired spectral-spatial gradients and residuals. Measurement strategies will become even more complicated as 2-dimensional gradient filters begin to make their way into the marketplace.

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