Measuring Sharp Spectral Edges to High Optical Density

M. Ziter, G. Carver, S. Locknar, T. Upton, and B. Johnson, Omega Optical, Brattleboro, VT

ABSTRACT

Interference filters have improved over the years. Sharp spectral edges (> 1 db/nm) reach high optical density (OD > 8) in a few nm. In-situ optical monitoring to within 0.1 % error enables these levels of performance. Due to limitations related to f-number and resolution bandwidth, post-deposition testing in typical spectrophotometers cannot reveal the quality of today's filters. Laser based measurements at selected wavelengths prove that blocking above OD8 to OD9 is manufacturable with high yield. This paper compares modeled spectra and laser based measurements.

INTRODUCTION

The advances in thin-film design software and automated, computer-driven deposition systems have made it possible to create the most demanding optical filters. It is not unusual for filters with cut-on and cut-off edges to exceed 2 OD/nm in steepness. The cut-on (50 % transmission) to OD 6 transition can occur within as few as 60 cm^{-1}. [1] These types of filters are commonly used in laser applications where the signal of interest is very close in wavelength to the laser line, such as Raman spectroscopy. Another application is the very narrow atomic line filter (such as the H-alpha) used in astronomy.

The OD (or blocking) of a filter depends heavily upon the application. Of course, the OD required for a particular application is a function of the intensity (J/s) of the light one is trying to block (interfering signal) and the integration time of the detection system. For instance, in a system with a uJ/s interfering signal and an integrated detection time of 0.1s, an OD of 11 gets the interfering signal below the 1 photon limit. In contrast, when a much shorter integration time is used (on the order of 100 ns), an OD of 5 is sufficient to reach the 1 photon limit. Other factors should also be considered by the customer, including the wavelength range of the required blocking, peak blocking versus average blocking over that range and price.

Design of these types of filters present a challenge as the manufacturer has to balance several factors, the first of which is a trade-off between a very steep edge and ripple in the passband. For a dielectric stack of a given number of layers, reducing ripple at the transmission peak causes a decrease in the edge steepness. This tradeoff can be countered by increasing the total number of layers, but then other factors such as the length of the deposition and stress in the films become more important. Film stress (especially in thick >10 micron stacks) can be large enough to warp the substrate [2, 3], while exceedingly long deposition times reduce manufacturability and increase cost.

Once a design is developed and deposited on a substrate, the manufacturer is faced with the limitations of the test equipment at hand. Most thin-film companies are equipped with scanning spectrometers which employ a grating or prism and slits. While convenient, the nature of these scanners introduces a wavelength broadening of the measurement equal to the spectral bandwidth of the instrument. Use of a broadband source will always lead to a distribution of wavelengths coming through the slit. This will manifest itself as a decrease in measured edge steepness as the transmission of the very steep edge filter under test is convolved with the spectral bandwidth of the spectrometer (Figure 1). The typical strategy is to reduce the slit size, but this reduces the incident light intensity, which in turn limits the OD that can practically be measured.

To further complicate the measurement in a standard scanning spectrometer, many sample chambers contain a convergent beam geometry that produces a number of angles of incidence (AOI) with the sample. Most thin-film optical filters are designed to work at a single AOI. The peak transmission wavelength of a bandpass filter designed to work at normal incidence will be shifted to lower wavelengths at other AOIs (Figure 1). The band shape may also be distorted at other angles because of polarization effects. The spectral AOI-dependence in the sample chamber is difficult to model because the AOI range in the horizontal and vertical directions are often different in the sample chamber. One strategy has been to aperture down the beam in the sample chamber to reduce the number of AOIs hitting the sample. This again reduces the incident light intensity, thus reducing the measurable OD. At very low light levels, one also approaches the detector's noise floor.

56th Annual Technical Conference Proceedings, Providence, RI April 20–25, 2013 ISSN 0737-5921

This is the main reason most spectrometers will not read above about 6 OD.

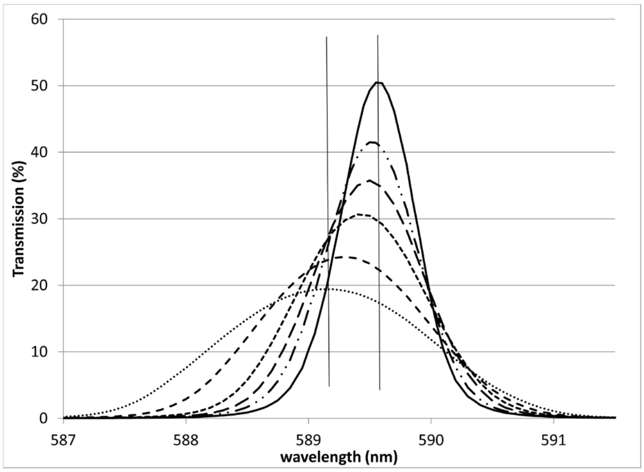

Figure 1: Measurements of thin-film optical filters are influenced by the spectrometer settings. A bandpass filter measured at 6 spectral bandwidths ranging from 0.1 to 2 nm. Broadening is caused by the increase in spectral bandwidth while the center wavelength shift (vertical lines) is due to an increase in the AOI distribution when the larger slit is used.

In theory, one should be able to deconvolve the measured spectrum using the instrument response function (a function that includes both the spectral dispersion and angular dispersions described above) to give a "true" spectral response of the filter. However, in order to do the deconvolution accurately, one has to measure the instrument response function directly. This is extremely difficult and adds noise to the measurement which complicates the deconvolution process.

While the AOI-dependence of a filter is a nuisance in a spectrometer, it can be used to explicitly measure spectral edges with a laser. [4] By rotating a filter in the laser beam, the transition edges can be "rocked" into transmission or reflection as illustrated in Figure 2. Edges always shift to the blue at larger AOI. This can be exploited to measure filters in the entire visible wavelength range using a small number of discrete laser wavelengths. If the edge is above the laser wavelength and within about 50 nm, the filter can be rotated until the light passes through (or gets blocked) by the impinging light (Figure 2). This method utilizes a fixed, linear polarization and a single wavelength. Contamination by other states of polarization cause an increase in the background signal and limits the measurable range. A properly polarized laser allows for measurements up to 9 OD where the detector reaches the noise floor.

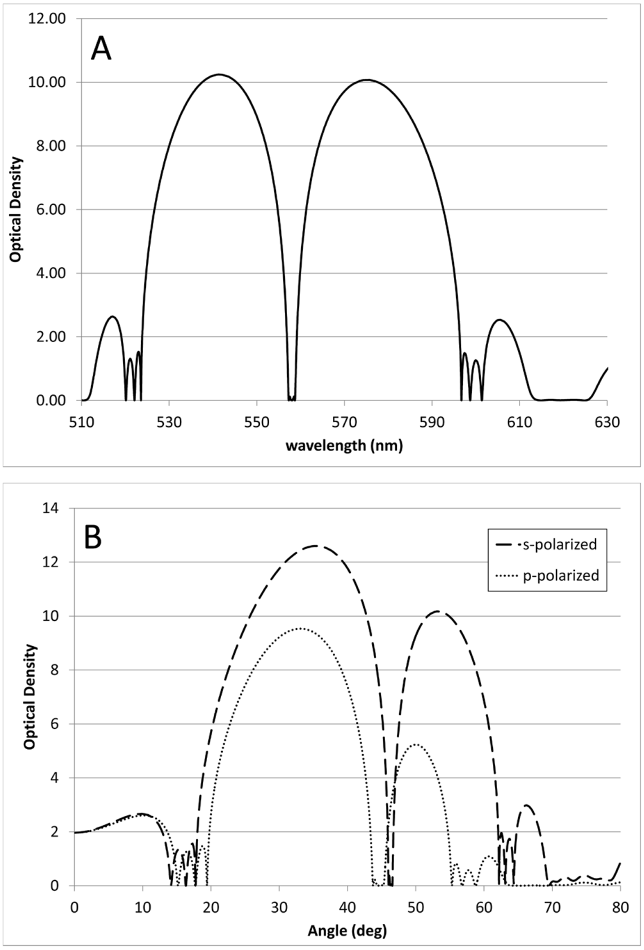

Figure 2: A Fabry-Perot design of 54 layers showing (A) the expected spectral response at normal AOI and (B) the expected AOI response at 514.5 nm. Note that there is a difference in the response of the two polarization states

In this paper, we detail a method that combines a number of spectral scans, angle rocking curves and thin-film modeling to predict the response of the deposited film to very high ODs-beyond the measuring capabilities of most optical systems.

MATERIALS AND METHODS

A 54-layer Fabry-Perot design was deposited onto a glass plate using thermal vacuum evaporation. The system was detuned so that the spectral response across the plate was not uniform.

For the tunable-laser measurements, we used an Agilent tunable external cavity laser (model 81640A) fiber-coupled to a an OFR free-space u-bench and an Agilent optical power monitoring head (model 81624A). The wavelength was tunable from 1520-1630 nm. The linewidth was approximately 0.4 pm and the center wavelength accuracy was 2 pm. The ASE floor is estimated to be 40-55 dB below the peak power. The wavelength tuning and power meter output are controlled by a LabView (National Instruments) program developed in house.

For the laser-rocking curves, we used an s-polarized Spectra-Physics Ar^+ laser line at 514.5 nm. A rotary stage was used to rotate the sample at 0.5 degree increments. Measurements were made using a Newport power meter (head model 818-SL, meter model 1830-C). The MM3000 controller for the rotary stage and the power meter are controlled by an application consisting of a pair of synchronous co-programs developed in house using National Instruments' Windows/CVI.

THEORY/MODELLING

Starting designs were simultaneously reoptimized to match the output of 3 spectrometer scans (at normal and 45 deg AOI over the range of 300-2500 nm with a 2 nm slit and at normal incidence from 500 to 600 nm with 0.5 nm slit) and the tunable laser scan. This large dataset was used because it provides complimentary pieces of information. The spectrometer scans provide a large wavelength range at relatively low resolution, while the tunable laser scan provides a small wavelength range at high resolution. The optimizaton was performed using the "reverse engineering" mode of the Essential MacLeod software. All 3 parameters (thickness, density and inhomogeneity) were adjusted sequentially until convergence. The fully converged reverse engineered design was then used in a simplex optimization using the rocking curve data, laser scan and the normal AOI spectrometer scan as targets. Spectrometer readings below 0.05 %T were set to zero. The rocking curve and laser scan were weighted more heavily because of their higher precision. Data values greater than 6.5 OD were set as a lower limit for the analysis so the model was free to converge at much higher OD values than measured. The Essential MacLeod software does not allow for rocking curve data input in the reverse engineering mode.

RESULTS

Figure 3 compares the output of the spectrometer to the tunable laser for a Fabry-Perot design containing 54 layers. The figure also includes the results of the design modeled to fit the spectra as described above. The starting design for the model (and deposition) was the same as in Figure 2. When the AOI is restricted in the spectrometer using an aperture, the lower incident light levels reduce the measurable OD to about 4.5 (Figure 3 dashed trace). Using the brighter tunable laser source (black trace) allows measurements up to about 6 before the detector approaches the noise floor. The narrow laser-line width allows fringes from the front and back surface of the substrate to be visualized. The dotted model indicates that this filter has an OD of 10 in the out-of-band region.

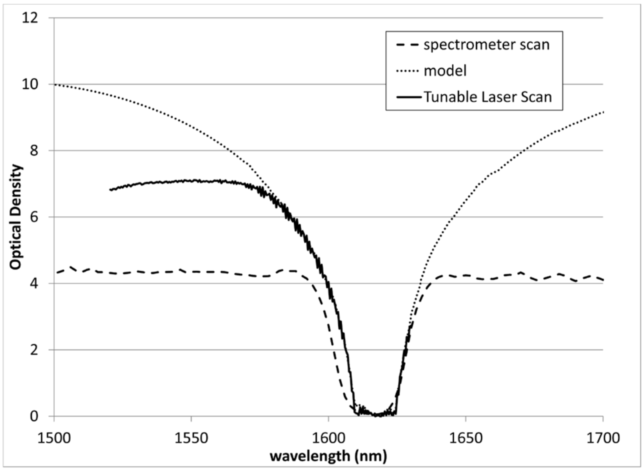

Figure 3: Comparison of different measurement methods. Dashed- output from the spectrometer with an aperture to reduce AOI effects. The spectral bandwidth was approximately 2 nm. Black- measurement with a tunable laser source. Dotted- data modeled using the Essential Macleod software.

Figure 4 illustrates the spectral inhomogeneity in the detuned deposition system. This filter was designed to transmit in wavelengths that are compatible with both our tunable NIR laser and visible rocking curve setup. The first-order transmission band occurs at about 1618 nm (Figure 4A), while the third order transmission occurs at about 557 nm (Figure 4B). In the middle of the plate (center, Figure 4A, B), the transmission is high with steep edges. The transmission collapses as a function of radius. The collapse is more dramatic in the third order (Figure 4B). In contrast, the measured OD (Figure 4 C,D) is above the measureable limit of about 7 OD for the tunable laser measurement (first order) and about 9 OD for the laser rocking curve (third order) for all measurements, regardless of where on the plate they were measured.

Because the measurements on the plate cannot exceed about OD 9 with either laser-measurement system, the filter designs were modeled using the spectral and rocking data to give the results in Figures 3 and 5. In the first order, the model of the center of the plate gave very high ODs (up to 10- Figure 3), as did the 3 inch radius (up to 9- Figure 5A). In third order, models of the rocking curve (Figure 5B) also show very high ODs (over 12) in both the center and 3 inch radius measurement. Figure 6 illustrates the percent change in refractive index and physical thickness in each layer of the stack between the 3 inch radius and the center of the plate as modelled with the Essential MacLeod software. In most cases, an increase in the refractive index is coupled to a decrease in physical thickness (or vice versa) as expected. Notable exceptions occur in layers 13 where they both increased and 47 where they both decreased significantly.

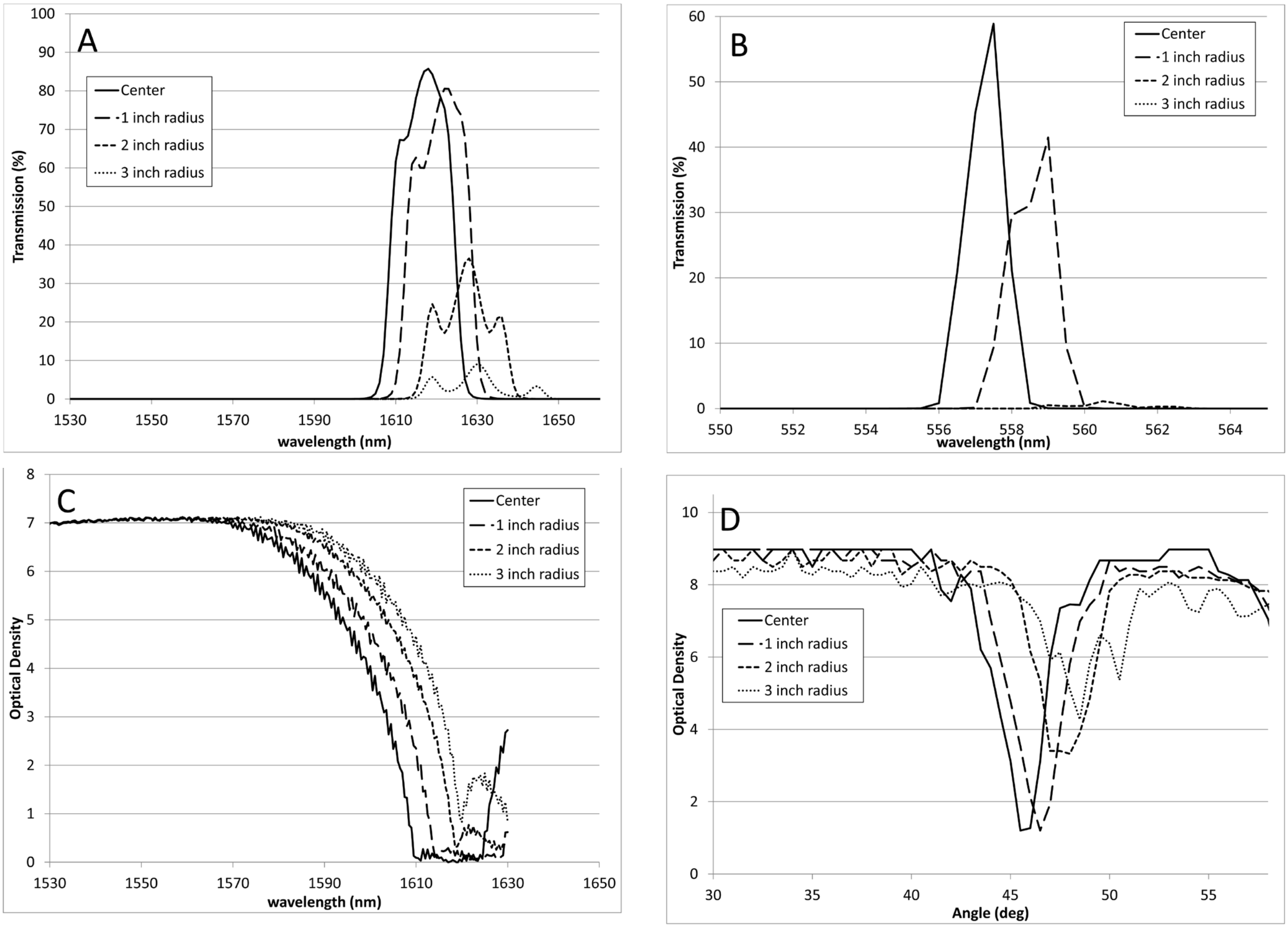

Figure 4: A thin-film stack shot on a detuned deposition system. A and C are the output from the spectrometer and laser scanning system respectively. B is the output of the 3rd order peak from the spectrometer. D is the rocking curve using an s-polarized 514.5 nm laser.

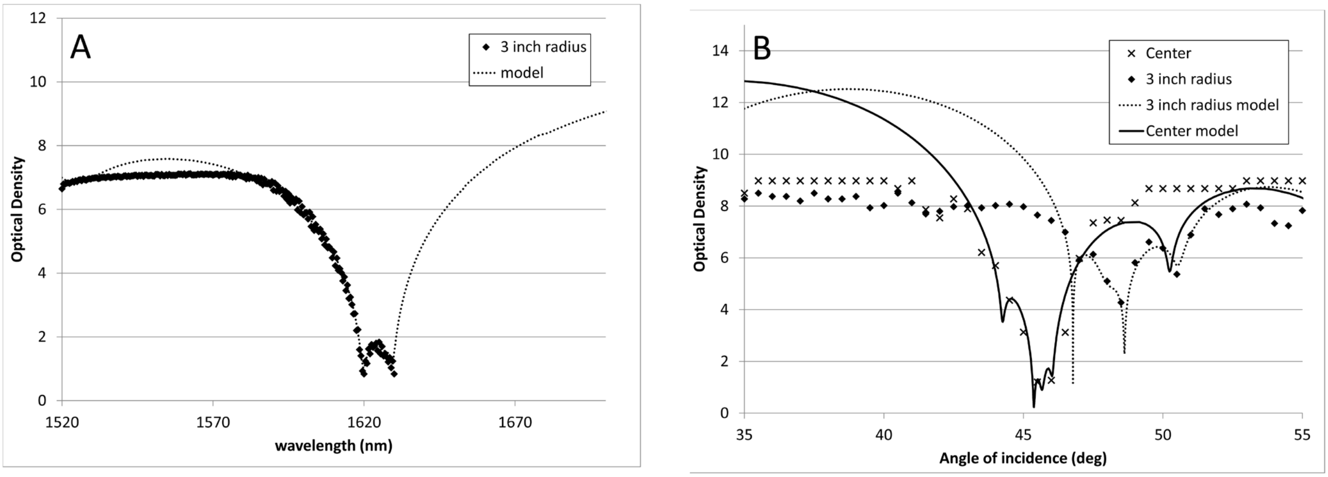

Figure 5: Model versus spectral trace and rocking curves. A. Model versus laser scan for 3 cm radius in first order B. Model versus angle scan for center and 3cm radius in third order

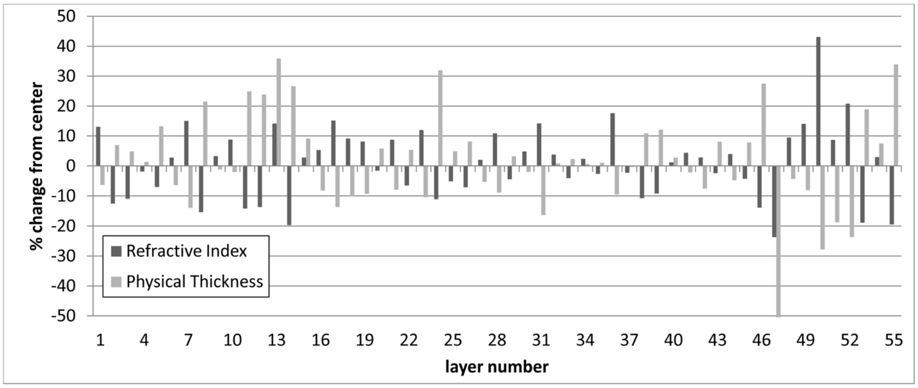

Figure 6: Modeled thickness and refractive index variation between center and edge.

DISCUSSION

Tunable lasers are available in a number of wavelength ranges. This sort of light source offers advantages over a scanning spectrometer. First is that the spectral bandwidth is defined by the laser linewidth (a function of the cavity design) and not a slit. Typical linewidths in these types of lasers is sub-picometer. A spectrometer can approach sub-angstrom linewidths, but the intensity becomes so low that measurements are impractical (Figure 3). These lasers do exhibit an ASE emission that is roughly 40-50 dB down from the peak, but our measurements down to OD 7 suggest this is a minor source of error. The other advantage of a laser source is that it is much easier to collimate, resolving the AOI issue present in scanning spectrometers. These properties enable us to directly measure the steepest of transitions. It also gives a very accurate measurement to use in the modeling of higher OD values.

Using the rocking curve at a set laser wavelength to characterize filters is another approach that is not widely used or reported in the literature. The rocking curve is also an extremely sensitive technique that, because it is also laser-based, shares many of the advantages of the tunable laser measurement. The spectral bandwidth of the laser is very sharp and the beam is easily collimated. Single-wavelength lasers are also relatively inexpensive. The two laser techniques are complimentary (Figure 2) and the same lasers can be used for both.

Both techniques suffer from the intrinsic limits of the detector and cannot measure very high (> 9 or so) ODs directly. Of course, using a more powerful laser, a more sensitive detector and phase-sensitive or heterodyne detection [5] can push the detection envelope up to higher OD levels, [6] but there are always limits. Many modern filter designs have ODs up to 20 or more. Direct detection at these levels would introduce a myriad of problems including the non-linear optical effects of an extremely powerful laser source, localized heating or annealing of the filter, [7] the need for a dust-free environment or cleanroom to minimize background signals, etc. It is much more practical to model the filter to predict high-ODs that are beyond the measuring capabilities of a typical manufacturing environment.

In order to obtain a convergent model using the Essential MacLeod thin-film design software, one needs a good set of spectral and/or rocking data. Since there are a large number of variables (at least 3 per layer), the model is somewhat underdetermined. The models illustrated here are only two of several possible solutions. Regardless, the results of the model are informative. The fit to the major features of both the laser scan and the rocking curve is quite good. It also illustrates that the source of the transmission collapse across the plate is apparently not due to a systematic effect and appears to be due to random fluctuations in the plume of the evaporating materials. The large percent changes shown in Figure 6 are atypical for a well-tuned deposition system where spectral variations are typically less than 1 % across the plate. It also illustrates that a large perturbation to the transmission band causes a relatively small change in the blocking regions (high OD areas- Figures 3, 5). In a fast-paced production environment, the standard spectrometer measurement is adequate to identify a problem with the deposition. For the measurements of sharp spectral edges, the laser methods (rocking and tuned) are superior; extremely precise and accurate.

While the model predicts ODs up to and exceeding 10 units, in practice, small defects in the film, including microscopic pinholes and voids, will cause a lowering of effective OD. Even surface defects such as oil, fingerprints and dust can alter the interference effects of the stack just enough to reduce the effective OD at certain wavelengths. Pinholes can be easily identified with transmitted light microscopy using an appropriate filter or LED source.

CONCLUSION

Today's high-quality interference filters can be manufactured according to specifications that exceed our ability to measure the true performance. Typical spectrometers suffer from wide spectral bandwidth and AOI distributions that make accurate measurements of sharp spectral edges very difficult, but they are an excellent tool for the production environment. Production tests need to catch problems in a timely manner, which is the perfect application for a slit-based spectrometer. For measuring the sharpest edges, exquisite accuracy and precision are obtained by replacing the spectrometer with a laser-based measurement (either a tunable laser or a laser-rocking measurement). To estimate the true OD of the products (above the measurable OD 9), the spectral and laser-rocking data can be used to model the actual composition and spectral response of the manufactured filters.

REFERENCES

1. Omega Optical, "Optical Interference Filters for life sciences, machine vision, astronomy, aerospace", 2012, p. 55.

2. S. Jakobs, M. Lappschies, U. Schallenberg, O. Stenzel and S. Wilbrandt, "Characterization of metal-oxide thin films deposited by plasma-assisted reactive magnetron sputtering," *Chinese Optics Letters,* vol. 8 Supp., pp. 73-77, 2010.

3. F. Spaepen, "Interfaces and stresses in thin films," *Acta mater.,* vol. 48, pp. 31-42, 2000.

4. H. Macleod, Thin-film optical filters, 3rd Ed., New York, NY: Taylor & Francis Group, 2001, pp. 283-292.

5. A. Migdall, B. Roop and G. Xia, "Measuring filter transmittance using heterodyne detection," *Metrologia,* vol. 28, no. 3, p. 217, 1991.

6. T. Gentile, A. Frenkel, A. Migdall and Z. Zhang, "Neutral density filter measurements at the National Institute of Standards and Technology," in Spectrophotometry, Luminescence and Colour; Science and Compliance, Amsterdam, Elsevier, 1995, pp. 129-139.

7. C. Wolfe, M. Kozlowski, J. Campbell, F. Rainer, A. Morgan and R. Gonzales, "Laser conditioning of optical thin films," in Laser induced damage in optical materials; 1989, ASTM International, 1990, pp. 360-375.

8. Z. Zhang, L. Hanssen and R. Datla, "High-optical-density out-of-band spectral transmittance measurements of bandpass filters," *Optics Letters,* pp. 1077-1079, 1995.