Quantifying Display Coating Appearance

Modern displays often utilize anti-reflection coatings to enhance contrast and improve readability. However, display manufacturers have unique requirements for coatings not found in other industries. New metrology instrumentation has been designed to obtain the necessary measurements for display makers and to work with the thin glass substrates increasingly employed in display fabrication.

by Trevor Vogt

ANTI-REFLECTION (AR) coatings are often used on the outermost glass surface of flat-panel displays to reduce glare and increase visibility. But while AR coating technology has been utilized for decades with a variety of precision optics, including telescopes, camera lenses, microscope optics, laser components, and even eyeglasses, its use in display applications presents some challenges not encountered in those other applications. In particular, display manufacturers are often highly concerned with the apparent color and unit-to-unit consistency of the coating. Even slight variations in a thin-film coating that do not put it out of specification in terms of overall reflectance and transmittance values can change the reflected color in a way that is readily perceptible to the eye, thereby impacting perceived quality and value. These variations are common in AR coatings.

This article reviews the need for coatings and how they operate and explores the technology used for quantifying coating performance and color. Finally, we discuss the experiences of MAC Thin Films, a manufacturer of coatings for display applications, and show how this company implemented instrumentation from Gamma Scientific to successfully perform coating color measurement on a production basis.

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AR Coating Basics

A glass window forms the topmost layer of most commercial display types, including LCDs and AMOLED displays and virtually all types of capacitive touch-screen displays. Glass by itself reflects about 4% of incident visible light at each interface with air (with normal, 0° angle of incidence). Since the glass display window is invariably bonded to another material, usually a polarizer, this 4% reflectance generally occurs only at the outermost layer of the display. However, even this relatively low reflection is still sufficient to be visually distracting and can make the display substantially harder to read in high ambient light. To compensate for this, the user will often increase display luminance, consuming more precious battery power. The application of an AR coating to the top glass surface reduces the reflection to a much lower level and therefore improves both optical performance and battery life.

AR coatings consist of one or more thin layers of materials, typically dielectrics, which are deposited directly on to the surface of the glass. These layers modify the reflectance characteristics of the glass through the mechanism of optical interference, enabled by the wave properties of light. A simplified schematic of how this works is shown in Fig. 1.

The conditions shown in the figure for complete elimination of the reflection using a single-layer coating can only be exactly satis-

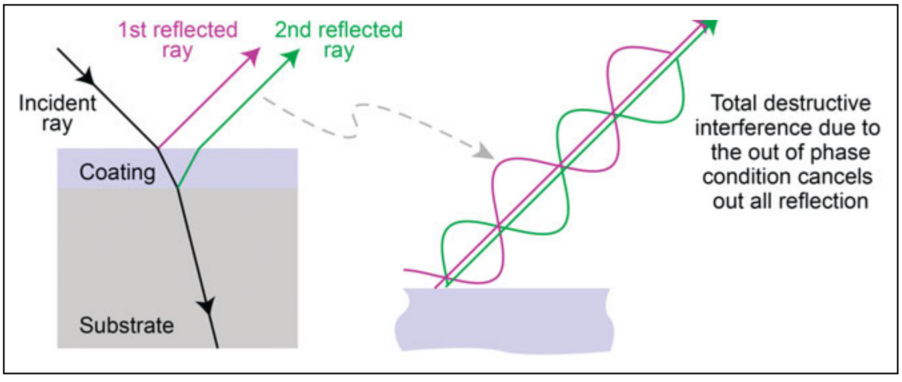

Fig. 1: This schematic shows a representative single-layer AR-coating operation.

fied at one wavelength and one angle of incidence. Thus, while single-layer AR coatings are widely used, thin films for more demanding applications often comprise multiple layers of various materials and thicknesses. These more complex multilayer designs can deliver higher performance and enable operation over a wider range of wavelengths and incident angles. They also permit the use of the most practical and readily available coating materials.

Coating Fabrication Challenges

There are a number of different technologies currently in use for producing the types of multilayer thin-film optical coatings just described. Typically, these involve converting a series of solid coating materials into vapor utilizing heating, sputtering, or some kind of chemical means. The process is performed within a vacuum chamber, and, in some cases, oxygen or other gasses are introduced to the chamber to react with the coating material and create new species. Once vaporized, the coating material eventually recondenses on the surface of the substrate in a thin layer whose thickness is carefully controlled. The use of different coating materials in series allows for multilayer films of substantial complexity and sophistication to be created.

Of course, any real-world manufacturing process experiences variations. For coatings, these are most significantly errors in layer thickness and variations in layer refractive index from the design goal. These small variations become particularly important in coatings for consumer display applications because cosmetic coating appearance is more important in this context than for most other uses.

A particular problem arises because virtually all AR coatings appear to have a color cast when viewed in reflection under white-light illumination. Furthermore, this color depends very strongly on the exact thickness and refractive index of each individual coating layer. Even slight variations in these parameters, which are not large enough to keep the coating from meeting its nominal reflectance and transmittance specifications, can significantly influence its visual appearance. Thus, it is common to see batch-to-batch variations in reflected color for a given AR coating design.

These variations in perceived coating color are particularly objectionable to display manufacturers who want a product that is visually consistent from unit to unit and that conforms to cosmetic standards congruent with brand image. For example, manufacturers want to be able to display their products side by side in retail stores without the consumer seeing obvious differences in color (whether as a result of coatings or other causes).

Color-Measurement Basics

For the manufacturer, the first step in controlling coating color is measuring it accurately. The schematic of one type of system for quantifying surface reflectance is shown in Fig. 2. In this instrument, called a goniospectrophotometer, a light source is focused at a non-normal angle of incidence onto the surface

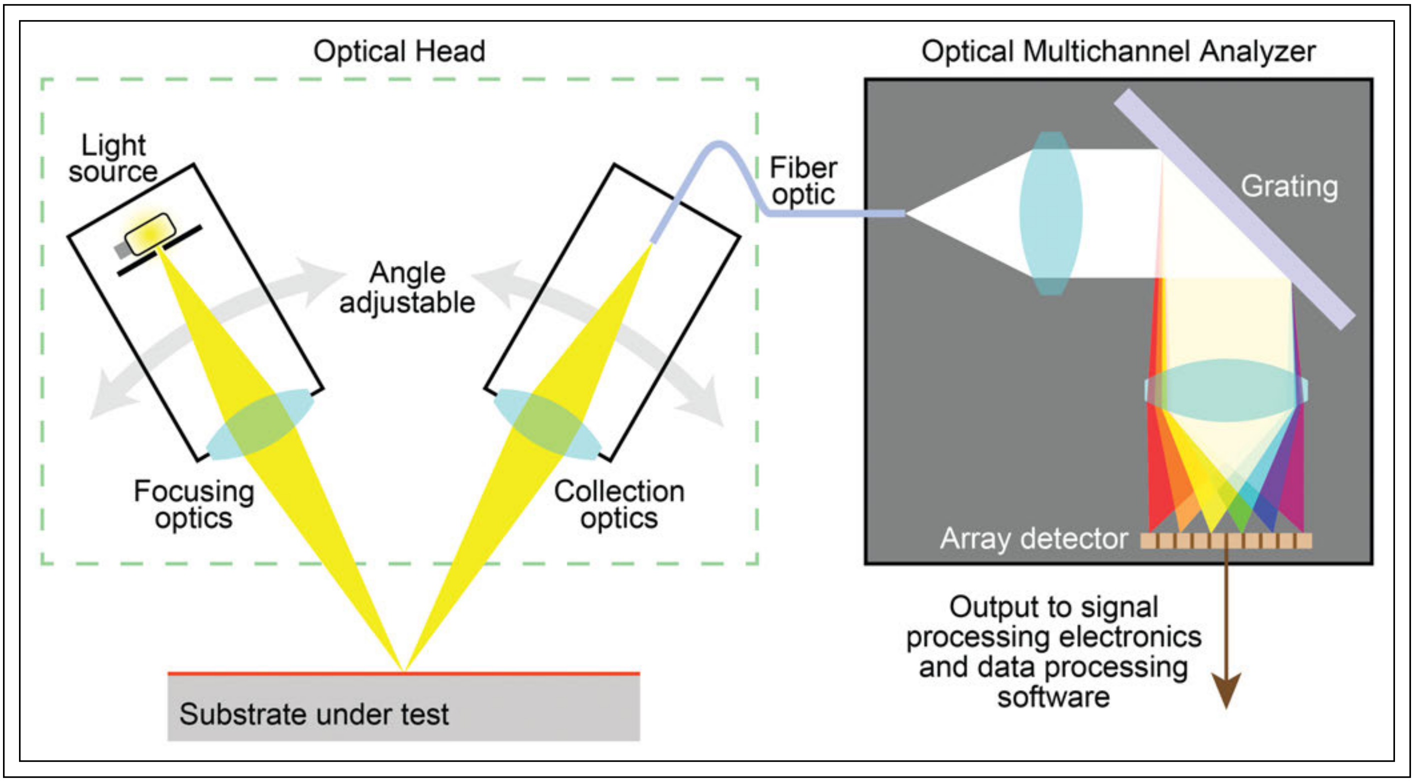

Fig. 2: *The main functional optical elements of a goniospectrophotometer include (left) optics for focusing a light source onto the device under test and collecting the reflected light and (right) a dispersive element and array detector that enables the spectral content of the collected light to be analyzed.*

under test. In order to make measurements that span the entire visible spectrum, a broadband light source, such as a halogen bulb, is used.

Collection optics are positioned exactly opposite the source angle of incidence in order to collect specularly reflected light (as opposed to scattered light). The gathered light is then focused into a fiber-optic cable. Sometimes the positions of the focusing and collection optics can be mechanically adjusted along an arc, centered on the surface under test, to enable measurements at a variety of incidence angles.

The fiber feeds into an optical multichannel analyzer (OMA). This is a type of spectrumeter that uses a diffraction grating to split the broadband input light into its spectral components. This light is then focused onto the equivalent of a 1024-pixel linear-array detector so that each element of the array only collects light from a small band of wavelengths. This allows the instrument to make a rapid measurement of reflectance intensity as a function of wavelength over the entire desired spectral range all at once.

However, this spectral reflectance data does not quantify how an object appears to the human visual system (its perceived color). And even minor changes in the reflected spectrum can affect the human experience of color. Representing color in a way that correlates well with human visual experience requires working in a calibrated color space, such as those defined by the International Commission on Illumination (CIE). The radiometric spectral data from the OMA is, therefore, mathematically converted into colorimetric tristimulus values which can then be mapped into any one of the numerous CIE color spaces.

Advanced Coating Measurement Technology

Various embodiments of this type of goniospectrophotometer technology have been commercially available from a number of manufacturers for decades. This basic measurement engine design is effective and well-proven. However, all past commercial products have had some combination of practical limitations that prevented their use in high-volume industrial inspection applications such as display metrology.

One significant drawback of most commercial goniospectrophotometers is that their optics collect light from several of the many closely spaced multiple reflections that occur in a glass component, when all that is desired is the first reflection from the top surface (see Fig. 3). This is particularly problematic when measuring AR coatings on an individual glass substrate because the signal from the top (AR coated) surface is much smaller than the unwanted returned light from the uncoated bottom surface. Note that these multiple reflections do not occur when the glass is integrated into a tablet or cell-phone display because then the bottom glass surface will be in contact with another material (usually a polarizer) having a similar index of refraction. Rather, this issue only occurs when attempting to measure the glass substrate after coating, but before it is integrated into the display assembly. This is a specific application challenge because the testing is performed by the cover-glass manufacturer, not the final display integrator. At point of test, the glass manufacturer has no access to the polarizer or the other display components that will eventually be used with it. But manufacturers still need to ensure that the glass they produce will deliver the necessary performance in the final assembly. Thus, they need to suppress the second surface reflectance (because the polarizer will eliminate it in the final display assembly) and measure just the first surface reflectance.

The reflection from the bottom surface can be reduced or eliminated by covering it with an absorptive paint or by placing that surface in contact with an index-matching fluid. However, both of these approaches introduce extra steps into the measurement process (painting, cleaning, *etc.*), often representing an unacceptable increase in production costs for high-volume fabrication.

Alternately, some instrument makers do not suppress the second surface reflection, but instead use a mathematical algorithm to subtract it from the measured data. Unfortunately, this indirect approach requires that assumptions be made about the refractive index and absorption characteristics of the glass under test, which cannot easily be verified. This method therefore substantially limits results accuracy.

A more ideal solution is to introduce some sort of spatial filtering into the collection optics. This takes advantage of the fact that, at other than normal incidence, there is a small lateral displacement between the desired top surface reflection and the other multiple reflections. Thus, the unwanted light can be physically blocked out.

This approach delivers superior accuracy, especially for AR coatings, and does not increase measurement cost or reduce measurement speed. And, importantly, this method can be successfully applied with glass

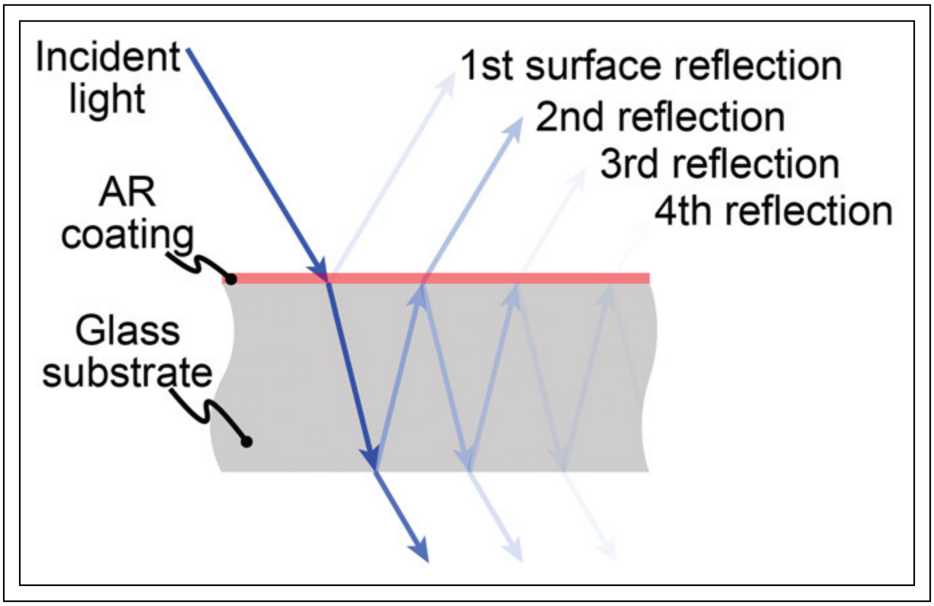

Fig. 3: Light striking a glass plate at an angle undergoes multiple reflections.

substrates having thicknesses as low as 0.5 mm. This is critical because thin glass is finding increasing use in displays.

The other significant limitation of many goniospectrophotometers is that they are designed for laboratory use rather than for in-line production environments. Typically, they can only measure a small (usually 2 in. square) witness sample. Furthermore, their measurement speed (several minutes) is not always sufficient to keep pace with production processes.

Gamma Scientific has recently developed new technology to address these shortcomings simultaneously. Specifically, its goniospectrophotometers all incorporate spatial filtering to suppress second surface reflectance and deliver highly accurate measurements (Fig. 4). Spatial filtering takes advantage of the fact that, at non-normal angles of incidence, the (unwanted) second surface reflection is laterally displaced from the first surface reflection. An appropriately sized aperture, also called a spatial filter, can therefore be placed into the beam path to block the second surface reflection, preventing it from entering the OMA.

Additionally, the measurement speed has been reduced from seconds down to milliseconds through the use of use of a highly efficient optical design and the CCD-array detector in the OMA. The detector employed is of a type referred to as "back-thinned," which offers increased sensitivity and shorter exposure times than front illuminated detectors. In a conventional front-illuminated CCD detector, the pixel drive circuity is on the top side (where the light comes in). This circuitry reflects some of the incident light causing a reduction in signal, and hence reducing device sensitivity. A back-thinned sensor is just as the term implies – the silicon-wafer substrate of the CCD is reduced in thickness during fabrication, allowing the finished sensor to be used with light entering the back rather than the front side. Thus, the light does not have to pass through all the driver circuitry. This can improve the chance of an input photon being captured from about 60% to over 90%, thus substantially improving sensitivity. Thus, back-thinned sensors are often employed in low-light optical measurement applications.

These instruments have also been optimized to test substrates of essentially any size in line, and they can be configured with motion control and part-handling hardware to support fully automated operation. This is possible because these systems are not configured like conventional spectrophotometers, which are self-contained instruments into which the operator places a small (typically 2-in. square) witness sample in order to perform testing. Instead, the Gamma Scientific system consists of a goniospectrophotometer optical measurement head (as previously described) which sits over a large testbed. This testbed can be sized to allow parts of virtually any dimensions to be placed on it, and then positioned (manually or under motorized control) for rapid measurement.

The goniospectrophotometer acquires the spectral power distribution function (*e.g.*, reflectance as a function of wavelength) of the device under test, and then inputs this raw data into the tristimulus equations. This enables the calculation of color values for any arbitrary color space under any illumination conditions (most commonly D65). In turn, this allows the visual appearance of the part, under any lighting conditions, to be determined.

Another key aspect of the system software is that it performs a non-linear regression on the measured data. In order for this to work with an optical coating, the system is originally programmed with a model of the nominal coating design (*e.g.*, layer thickness and refractive indices) and also given information on which parameters might vary in actual production. When a part is measured, the software can then determine its likely coating parameters. Thus, if a coating is not performing to specification, the system is able to identify which coating layer(s) are in error, and the particular nature of that specific error (*e.g.*, incorrect thickness). This enables the manufacturer to rapidly identify and correct specific problems with its process without any guesswork.

The system software is originally configured by an engineer or R&D person with technical expertise who inputs all the process parameters. They can also determine how the data will be displayed to production personnel and set pass/fail criteria for virtually any measured parameter (spectral power distribution, color, various layer parameters, *etc*.). Thus, production-line personnel can be presented with anything from detailed measurement

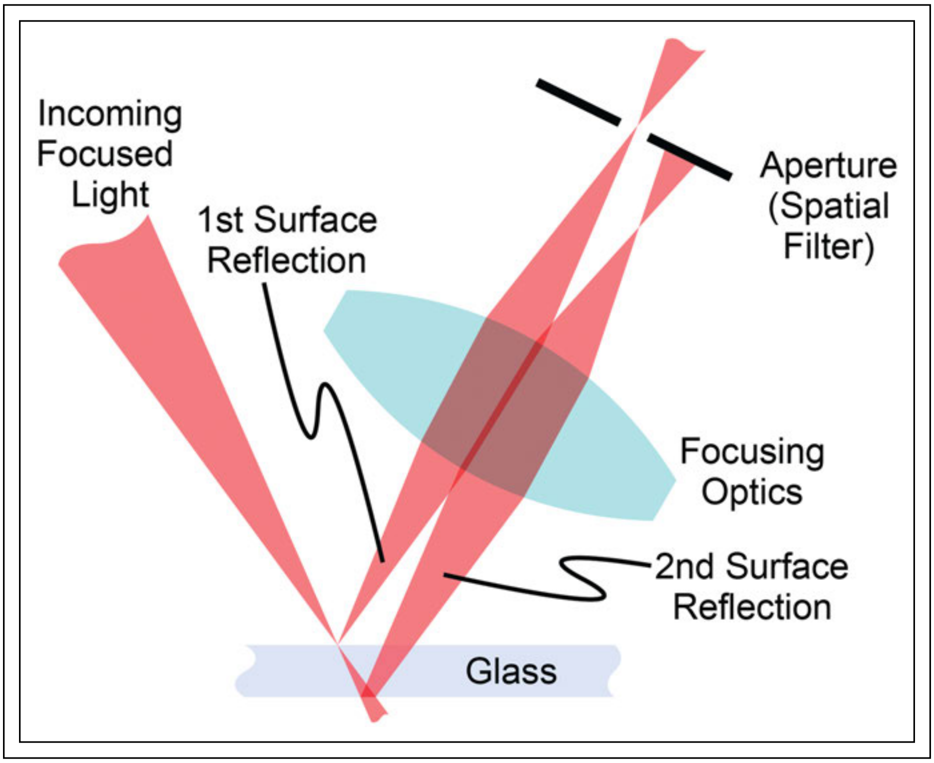

Fig. 4: *This simplified schematic shows the spatial-filtering technique used to effectively eliminate second-surface reflections from reflectance measurements.*

results to an extremely simplified interface that simply provides pass/fail results for any criteria of interest to the manufacturer.

Display-Glass Metrology at MAC Thin Films

MAC Thin Films, a manufacturer of high-performance mirror and AR coatings, recently began using a Gamma Scientific goniospectrophotometer for production screening of its coatings. The rest of this article describes how this enabled a dramatic difference in process capability.

MAC Thin Films employs a continuous process for multilayer thin-film coating. Here, the glass is loaded on to a conveyor belt and then transported into a series of airlock chambers where a progressively higher vacuum is drawn. Once at the appropriate vacuum level for coating, the glass moves through a series of deposition chambers, all of which are already evacuated. In each station, a single layer of coating material can be deposited. Finally, the glass enters another series of airlock chambers where it is returned to ambient pressure. As product advances through each stage of the system, new parts are being loaded and finished parts are being unloaded.

In this type of continuous processing, it is critical to know as soon as possible when any component of the process has gone out of specification. This is because the longer the delay before a problem is identified, the greater the number of out-of-specification parts (*i.e.*, scrap) that are produced.

The AR coatings for display applications produced at MAC Thin Films are usually specified to deliver less than 1% reflectance throughout the entire visible spectrum. Over the past several years, it has also become commonplace for customers to specify the apparent color of the coating as well. However, most customers do not start with a numerical specification for this, in terms of the coating's nominal CIE color coordinates and tolerances. Rather, MAC Thin Films usually determine these parameters through an iterative process with prospective customers, in which they are shown a series of samples and then pick out the range of ones that look acceptable.

For most customers, MAC Thin Films coats 32 × 50 in., or 25 × 32 in., substrates. These are subsequently cut down into individual pieces that are the size of the finished display. In the case of chemically strengthened glass, the pieces are supplied already cut to final size. The thickness of the substrates ranges from 0.7 to 10 mm.

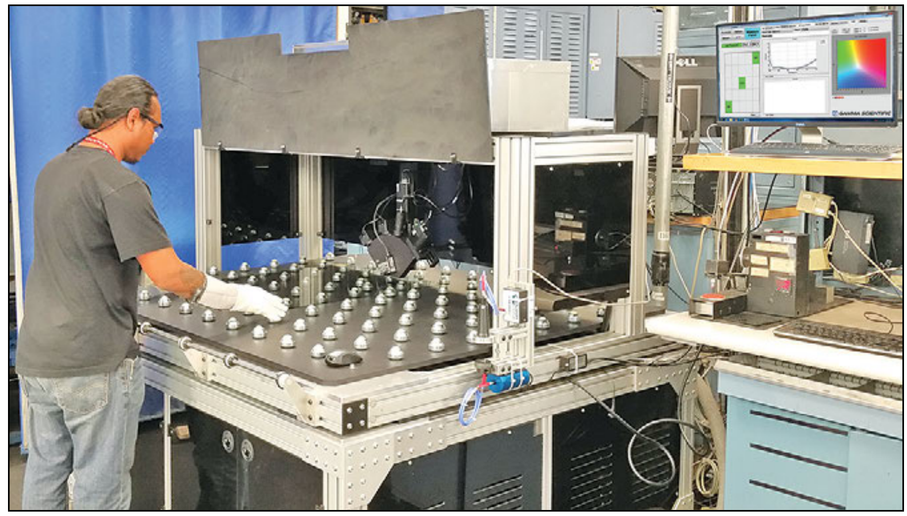

Fig. 5: A worker places glass onto a roller bed and then positions it under the optical head in order to perform a measurement. Photo courtesy MAC Thin Films.

During a typical production run, one piece is taken off the line every 10 minutes for inspection using the Gamma Scientific system. The process at MAC Thin Films is highly stable, so this level of sampling has been found to be adequate. For substrates receiving the Print-Free coating, a second set of color measurements are taken after that process too.

To perform a measurement, a technician first places the part by hand on the instrument's testbed. The system's optical head automatically acquires focus with micron-level precision which is critical for proper operation of the second-surface suppression optics. To achieve this precise focus, the instrument utilizes an off-the-shelf laser-based distance sensor, which is mounted on the goniosphectrophotometer optical head. The glass testbed itself is mounted on a high precision z-axis motion stage. A feedback loop is used to vertically adjust the height of the glass surface until it is at the correct distance from the optics, which have a known fixed focal distance. This eliminates any errors due to variations in glass thickness or mechanical placement on the testbed.

Once focus is acquired, which takes just a fraction of a second, a measurement is made. Typically, for a 32 × 50 in. substrate, the technician samples the part at three locations – the center and two diagonally opposite edges. Each measurement takes about 10 sec (Fig. 5).

Usually, the system is programmed to deliver a graph of reflectance as a function of wavelength and the color coordinates at each measured point. This is the data supplied to the customer. Additionally, the system software is set to display the results in a color coded, "go/no go," map which immediately alerts the operator when a part is out of specification. Furthermore, trend charting is used to indicate how the coating process is developing over time so that nascent problems can be identified and fixed before they result in the production of scrap product. The non-linear regression capabilities of the software are particularly useful in this connection because they allow the exact nature of any problems with the coating process (such as an error in layer refractive index) to be specifically identified.

In conclusion, sophisticated thin-film coatings are now a standard part of display fabrication for many applications. This technology, together with a greater emphasis on product cosmetics, has created a need for metrology equipment that can quantify both coating performance and appearance, and which delivers the speed and ease-of-use necessary for employment in today's production environments. ■