Comparative Experience in the Use of “Steering” in Automatic and Manual Optical Monitoring

R.R. Willey, Opto Mechanik, Inc., Melbourne, FL

Keywords: Optical coating; Process monitoring and control

ABSTRACT

Optical monitoring algorithms were previously described which gave some ability to partially correct for operator and/or process errors such as inaccurate layer terminations or index of refraction variations. These algorithms have been used in manual optical monitoring and also applied to two different automatic optical monitoring systems. We describe our experience with these three systems and the lessons learned. The experience has suggested that additional modifications to the algorithms might be beneficial, but that the basic algorithms provide good control at the monitoring wavelength and repeatability which is probably limited only by other factors in the processes.

INTRODUCTION

A great number of optical coatings are constructed from filters where the edge between the passband and the blocking band is one of the most critical characteristics of the coating. This includes longwave pass (LWP), shortwave pass (SWP) as seen in Fig. 1, and the type of bandpass (BP) filters which are made from a combination of a LWP and a SWP. This paper discusses how to achieve the goal of precisely controlling this critical edge position in wavelength and maintain high transmittance in the adjacent passband. In an absolutely stable process, this is not difficult, but real processes do have variations such as interruptions, malfunctions, rate changes, index variations, etc., etc. The “steering” technique and associated principles which we discuss provide some compensations for these errors and variations so that the production yield of these edge filters can be maximized. Steering is the correction for errors in the photometric level of turning points in the optical monitoring of layers of a periodic structure by small adjustments to the next cut point after the detected error.

HISTORY

We previously described[1] the benefits, general principles, algorithm, and details of constant level optical monitoring with “steering” and we referenced some of the key earlier work on which it was based [2-6]. Figure 2 illustrates the reflectance monitoring trace expected when all the layers are cut at a constant level.

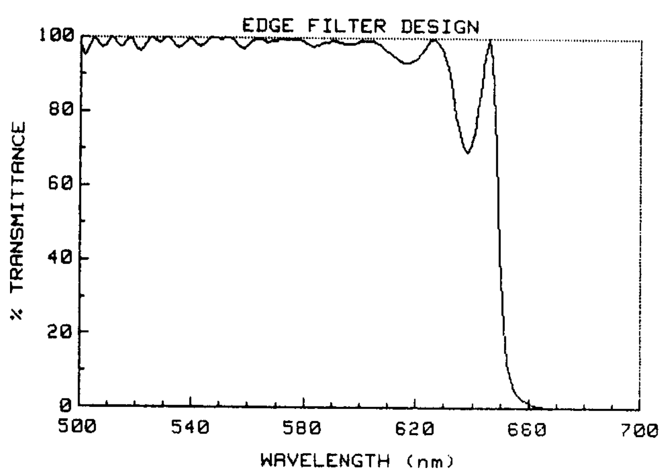

Figure 1. Design of a typical SWP edge filter.

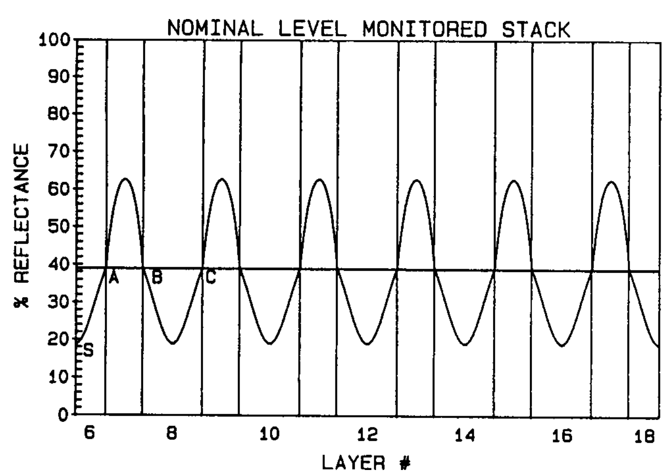

Figure 2. Predicted optical monitor trace for constant level monitoring where each layer is cut as it reaches the level at points A, B, and C.

Society of Vacuum Coaters 505/856-7188
37th Annual Technical Conference Proceedings (1994) 1-878068-13-X

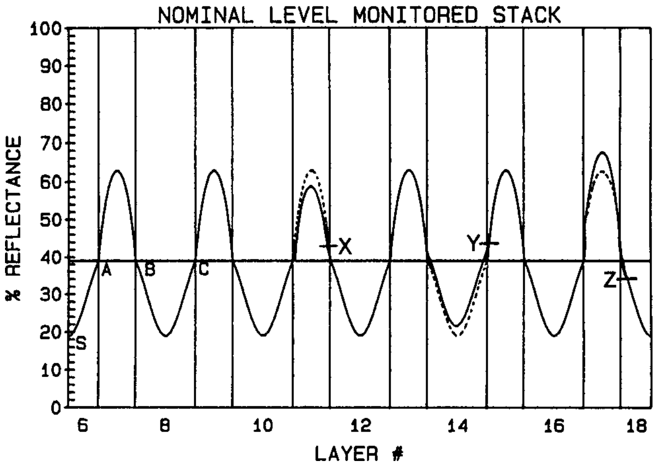

Figure 3. Steering corrections (X, Y, and Z) for turning values that are too low (layer 11) or are too high (layers 14 and 17).

Figure 3 shows how the cut points are modified by "steering" to correct for the errors sensed in the magnitude of the turning point of the layer being deposited. One key factor in the error compensation process is that all of the layers of the coating are deposited on one monitoring surface so that errors in previous layers continue to influence the monitor signal and may be partially corrected for by subsequent layers. Our work on the approximation of ideal index profiles [7] and what ideal index versus thickness profiles might be [8] has lead to the following hypothesis: the closer the optical monitor signal profile of reflectance versus thickness agrees with the design profile, the closer will be the reflectance versus wavelength profile to the design values. This is expected to be in best agreement in the spectral region close to the monitoring wavelength and to deviate more with distance from that point as shown by Zhao[4]. In the Fourier domain [8], this becomes somewhat more intuitive. If this is true, then it is desirable to control the magnitude of the reflectance swings of the monitor as well as the layer cut points. This is the principle discussion of this paper.

SOLUTION

We pointed out [1] as did Zhao[4] that it is expedient to monitor at a wavelength corresponding to the most critical spectral range of a given coating in order to have the maximum control over the most important part. "Keep your eye on the donut, not the hole." The best sensitivity is gained when all layers are cut at a reflectance as near to 36% as practical[6]. In order to do this, it is usually necessary to have precursor or precoat layers which bring the reflectance up from the substrate to the 36% cut level. In most cases of an edge filter and a passband, we have been able to design an antireflection (AR) coating of 3 to 6 layers which also brings the monitoring reflectance to the required value for the constant level monitoring. If we liken the "steering" of the monitoring to driving down a highway, the first layers are like the "onramp" of the highway. This is illustrated in Fig. 4. The starting design for such an on-ramp can be done by designing an AR from the substrate to a fictitious media whose index is $n=(1-r)/(1+r)$, where r is the reflectance amplitude desired at the constant level cut points. The fictitious media is then replaced by

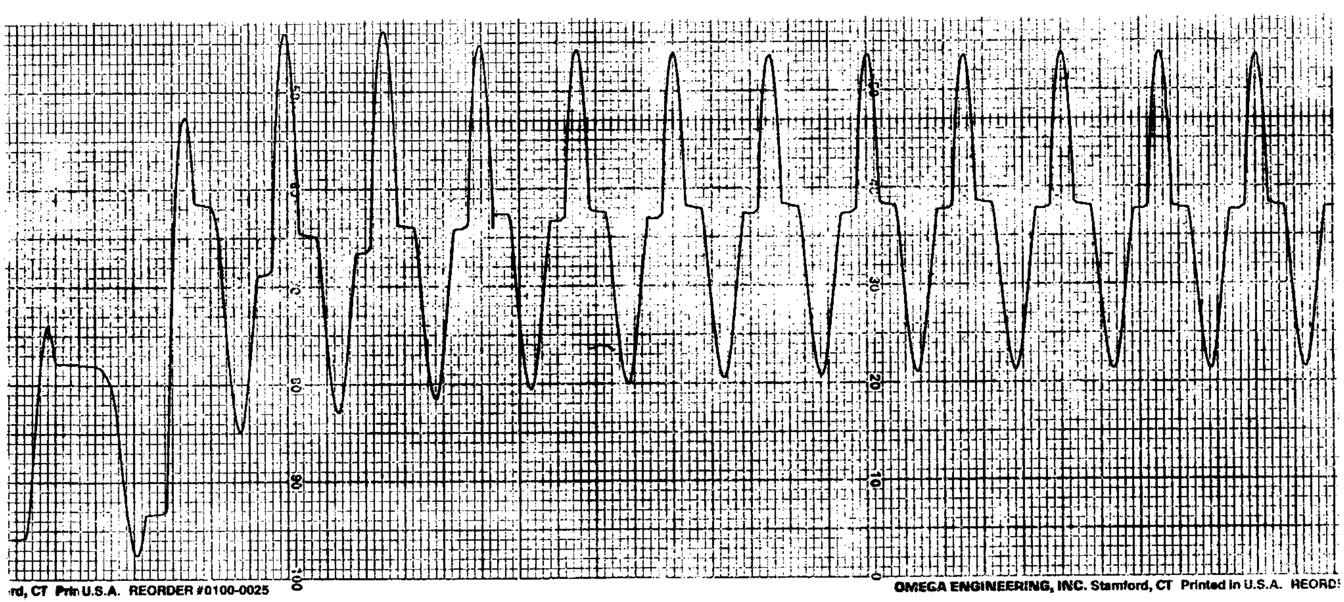

Figure 4. Actual optical monitor chart trace from test run on DynaVac system showing "on-ramp" layers and constant level cuts with steering. Note smooth transition of maxima and minima.

the periodic stack and small adjustments are made as needed to the on-ramp layers to give the desired constant level monitoring for the periodic part of the structure. It can be noted as in Fig. 4 that the transition in reflectance versus thickness from the substrate to the highway portion is generally bounded by an envelope which is a smooth contour within which the oscillations from minima to maxima occur. This looks similar and can be related to the quintic contours reported by Southwell, et al.[9] and our own studies of the basic nature of AR coatings[10].

LESSONS LEARNED

The steering techniques described were first applied in a Balzers BAK760 with an optical monitor by having the operators cut each layer at the appropriate level. This required the operator to observe the photometric level of the turning point for the layer and calculate (mentally or on a pocket calculator) the needed adjustment to the cut level. This was done with moderate success, but it can be tedious for the operator and divert his/her attention from other responsibilities during the process. The algorithm was installed on two newly acquired chamber control systems: the Denton DVOCS system installed on a refurbished Leybold A1100 (we refer to it as the "Denbold") and the latest control system on a new DynaVac 48 inch box coater. The automated systems reduce the operator tedium and are more consistent in results (as might be expected). The repeatability of the automated systems allows better fine tuning of the parameters from test run results.

With reference to Fig. 4, we will point out some requirements and observations. Unless otherwise stated, these observations apply in both manual and automatic cases. It is necessary to determine how much further in reflectance each type of layer will coast after the cut command is issued and then incorporate this correction in anticipation of each cut point. For the given high and low index materials, the changes in cut point needed to get an errant turning point back on track must be figured at the monitoring design stage. This is what we have come to call the "gain" factor[1] for the turning point errors of each material under the given design conditions. The target levels for the maxima, minima, and cut levels are all determined in advance from the knowledge of the indices, wavelength, and monitoring plan. These levels can be determined by the use of a thin film design program or other graphical methods. If the ratios of these three levels is in error, the proportions of the high and low index layer optical thicknesses will be in error and generate a "half-wave hole" in the transmittance which might not have been intended. This can be tuned in subsequent test runs by adjusting the cut level.

In the cases shown here, the monitoring is arranged such that the high index layers pass through a maxima. If the maximum is too high with respect to the target, the cut point will need to be lower than the nominal to get the next maximum to pass through the target level. This is the case illustrated in the third maximum of Fig. 5 which may have resulted from a spurious error in the cut of the previous layer. If a minimum is too high, the opposite is true, the cut will be higher than nominal. If the cut is made just right, the next layer after the cut will go exactly where it should (if the targets are correctly calculated from correct indices). The error, if any, in this next turning point can be used to tell if the gain of the most recent cut was too high or low. Changing the general cut level, as mentioned, will change to ratio of the high to low index layer optical thicknesses. It will also change the level of the maxima and minima. Lowering the cut level will raise the maxima and lower the minima (and vice versa). If the corrections become too large, the process can break down. For example, a turning point might be reached before the indicated cut level. This would not ordinarily be expected to happen in a well behaved process.

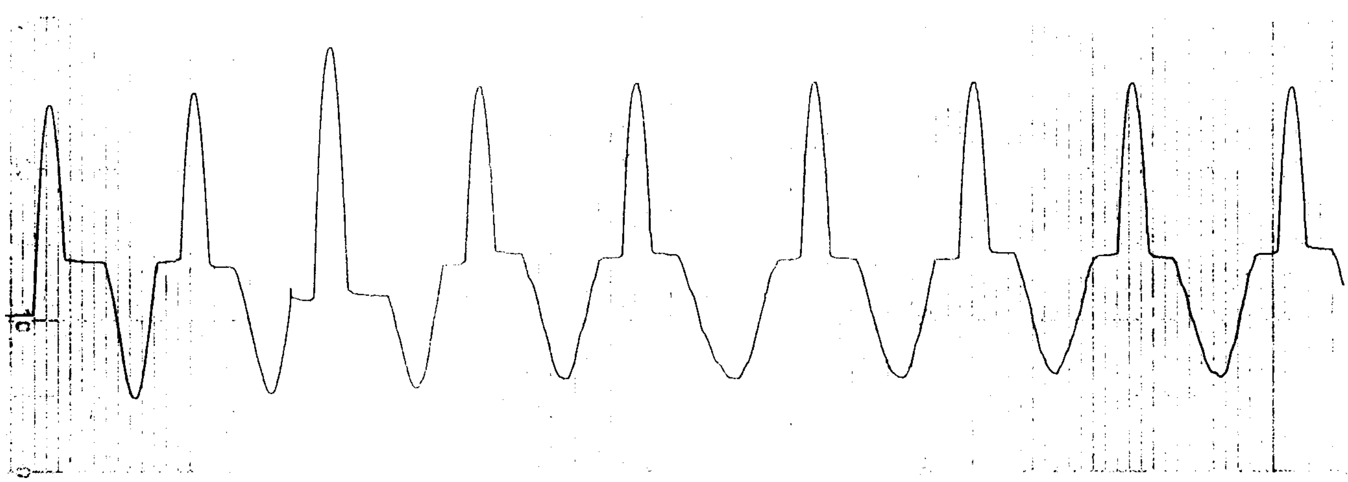

Figure 5. Example of automatic steering correction for the third maxima which was too high.

The photometric calibration of the optical monitor is important to the success of this technique because the exact wavelength of the edge of the passband depends upon the true values of the three levels in question. We currently use two different calibrations with the two different automated systems. In the DynaVac system, we use the reflectance of the uncoated monitor chip before any deposition as the reference for the photometric level. This is well known (4.1%R in our particular case) from the index of refraction of the monitor chip. This is the reflectance of the 0th turning point. In the Denton control system, the current software cannot use this initial value. In this case we use the reflectance of the turning point of the first TiO_2 layer. As long as the index of this layer is very repeatable, the calibration can be satisfactory, but we have come to prefer the bare chip method even though it is a factor of 6 or more lower than the first turning point.

The on-ramp layers use no steering, it comes into play at the 6th or 7th layer when the main highway begins. The extrema and cut points quickly settle in to relatively constant values if there are no perturbations as seen in Fig. 4. If the knowledge of the indices and photometric levels are correct, the steady state values will be as predicted. However, if there are differences from the expected index values, the values settle in to something different from nominal. We were surprised to discover that our centralized monitor chip was showing indices that were significantly lower than the parts being coated. This had to be taken into account. The resulting levels act like the stretching of a net to equalize the tensions between the target values, the actual values, and the force of the gain to correct the difference between them. This is also similar to driving down a highway with a strong crosswind. Constant pressure must be applied to the steering wheel to compensate for the force of the wind. Because of these and similar inaccuracies in available information, a reproducible edge wavelength may be achieved, but not at the correct wavelength. This can be corrected by adjusting the monitoring wavelength appropriately.

Figure 6 shows an example of the actual on-ramp and early layers of a steered run on the Denbold system. The input parameters to the algorithm were essentially the same as those used in the DynaVac which resulted in Fig. 4. The greater instabilities in the Denbold process illustrate how the steering attempts to compensate for those variations. Figure 5 shows the same effects in the DynaVac system. Figure 7 shows the repeatability of results of three successive runs in the Denbold using this algorithm which the Denton people named the "Willey Algorithm of Correction" or WACO.

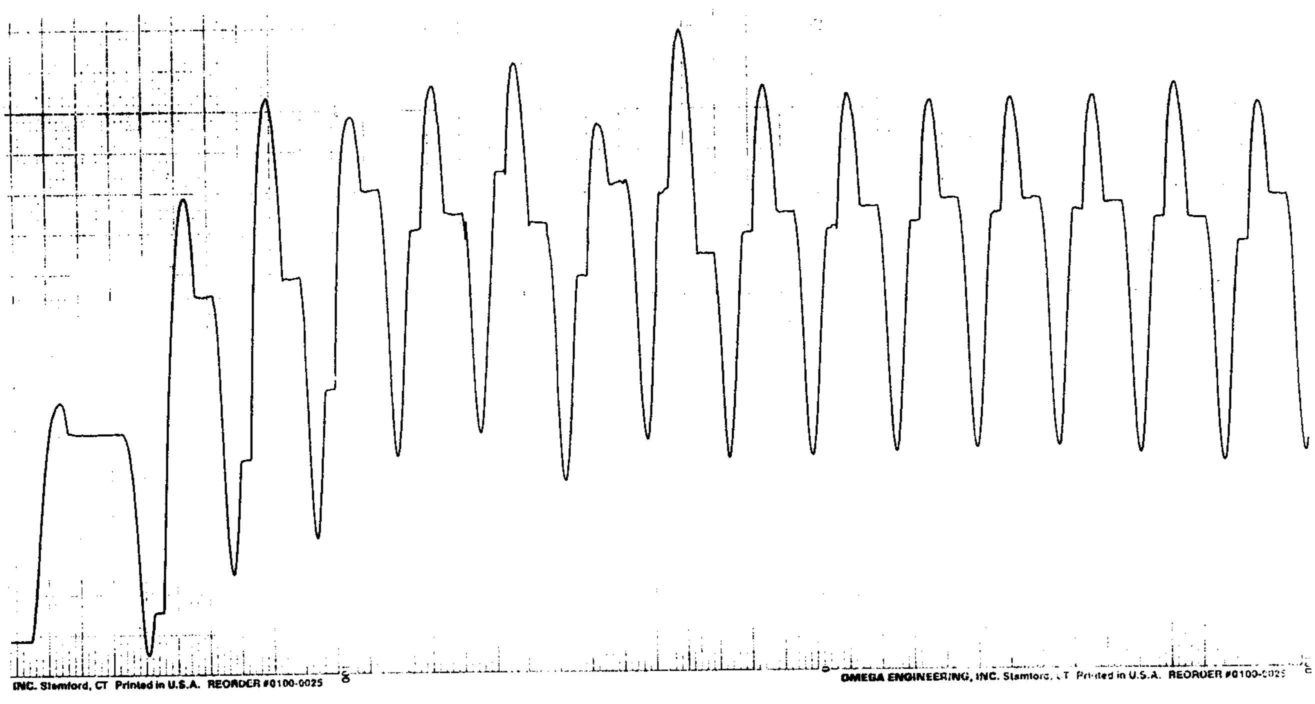

Figure 6. Actual monitor trace from Denbold system with similar conditions to Figure 4.

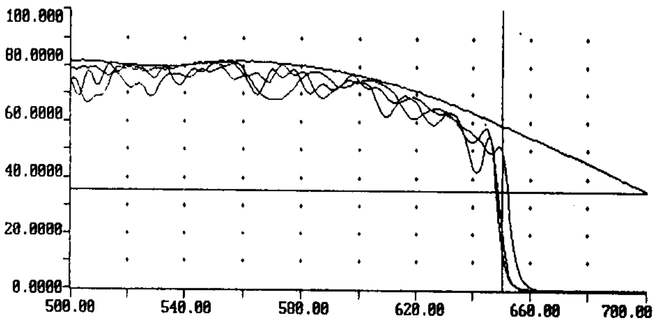

Figure 7. Spectral results of three successive runs in the Denbold system with the steering algorithm. Upper curve is uncoated substrate.

CONCLUSIONS

Our experience points to the fact that automated systems have a higher likelihood of achieving good yields on complex and lengthy coatings of the type described. The steering algorithm is helpful if not critical in both manual and automated systems, but the automated systems remove the pressure on the operator and are more repeatable. The steering technique compensates for typical process variations and tends to stabilize the results. We believe that the approach described here offers the best control known to date for the edge position and adjacent passband of an edge filter.

REFERENCES

1. R.R. Willey, "Improved Repeatability in the Production of Periodic Thin Film Structures by the Use of "Steering" with Optical Monitoring," Proc. Soc. Vac. Coaters 36, 156-162 (1993).
2. H.A. Macleod, "Monitoring of optical coatings," Appl. Opt. 20, 82-89 (1981).
3. H.A. Macleod and E. Pelletier, "Error compensation mechanisms in some thin-film monitoring systems," Opt. Acta 24, 907-930 (1977).
4. F. Zhao, "Monitoring of periodic multilayers by the level method," Appl. Opt. 24, 3339-3342 (1985).
5. R.R. Willey, "Optical thickness monitoring sensitivity improvement using graphical methods," Appl. Opt. 26, 729-737 (1987).
6. R.R. Willey, "Sensitivity of Monitoring Strategies for Periodic Multilayers," Proc. Soc. Vac. Coaters 30, 7-14 (1987).
7. R.R. Willey, "Graphic description of equivalent index approximations and limitations," Appl. Opt. 28, 4432-4435 (1989).
8. R. R. Willey, P.G. Verly, and J.A. Dobrowolski, "Design of wideband antireflection coating with the Fourier transform method," SPIE 1270, The Hague, (1990).
9. W.H. Southwell, R.L. Hall, and W.J. Gunning, "Using wavelets to design gradient-index interference coatings," SPIE 2046, 46-59 (1993).
10. R.R. Willey, "Basic Nature and Properties of Inhomogeneous Antireflection Coatings," SPIE 2046, 69-77 (1993).