Improved Repeatability in the Production of Periodic Thin Film Structures by the Use of "Steering" with Optical Monitoring

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ABSTRACT

An optical monitoring algorithm has been developed and implemented which improves the repeatability of results in the production of periodic optical thin film structures. The control and stability of the constant level monitoring technique has been augmented by the addition of "steering" to correct for errors as soon after detection as practical. When this is applied to single wavelength monitoring near the most sensitive wavelength, it has been shown in principle and in practice that the spectral results are improved. Some of the improvements include more repeatable spectral edge positions on edge filters and better pass band transmittance. The procedures have been successfully implemented both manually and in a computer controlled optical monitoring system.

INTRODUCTION

The basic problem addressed here is to obtain improved production repeatability in the edge position and high transmittance in the passband of a shortwave- (or longwave-) pass filter. Figure 1 illustrates a typical example of this type of filter. These are relatively easy to design, but can be difficult to fabricate if the requirements are +-5nm for the position of a 650nm edge. We have not been able to achieve this kind of result by using only crystal monitoring. Direct optical monitoring has been found to be necessary.

Macleod[1] provided an excellent overview of monitoring techniques and the earlier work of Macleod and Pelletier[2] provides the basis of what we call constant level monitoring. Zhao[3] further elaborated on using the constant level technique to obtain improved control over the stated problem. Zhao briefly mentioned the real time correction of errors based on the observation of the actual turning values as compared to the expected values. This procedure is what we have implemented and it has been used to solve the stated problem, and that is the subject of this paper.

Zhao[3] made it clear that the control of the spectral result is best in the region of the monitoring wavelength and will diminish with increasing distance from the monitoring wavelength. Figures 2 and 3 are taken from Zhao and show this effect. In the cases of interest in this paper, the edge position is critical and the passband transmittance for photopic (visual) light must meet a certain minimum. This means that the performance at 650nm and the region around 555nm are both important. We have described how to select the montoring wavelength for optimum sensitivity in general[4] and in particular[5] for edge filters. In this case, we choose to monitor between 600 and 630nm for best control of both requirements.

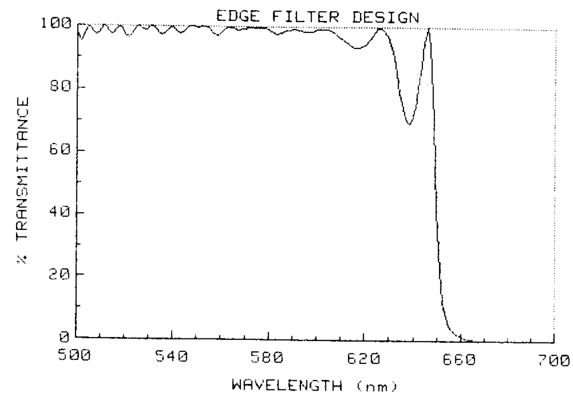

Fig. 1. Typical example of an edge filter design of the form discussed in this paper.

Basic constant level monitoring is illustrated in Fig. 4 where low index layers are terminated after passing a minimum turning point and when the optically monitored reflectance at a given wavelength reaches a specific level, (A). The next high index layer is terminated after passing a maximum turning point and reaching the same reflectance level as the previous termination, (B). This is repeated for as many layers as needed (C, etc.).

DEPARTURES FROM IDEAL

If the photometric levels are correct, stable, and have been chosen correctly, and the monitoring wavelength is at a high sensitivity point, and the index of the layers is constant, and the monitor spectral bandwidth is sufficiently narrow, etc., constant level monitoring works very well. However, in the real world, it is usually found that after many layers the process diverges or converges out of control. The probable causes of these instabilities are defects in the knowledge of the actual

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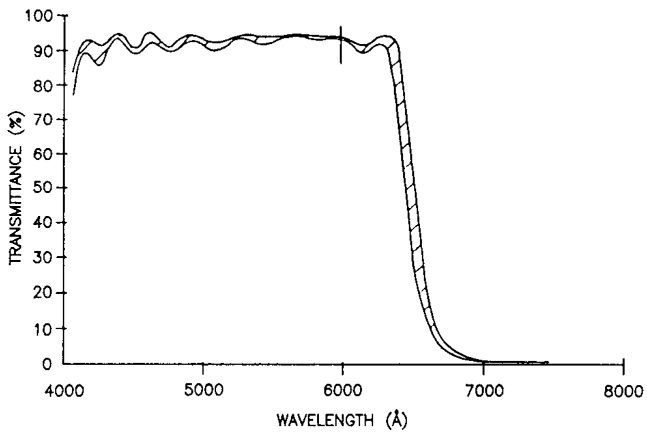

Fig. 2. Result of constant level monitoring error compensation from Zhao[3] when monitor wavelength (vertical bar) is near the edge of the passband.

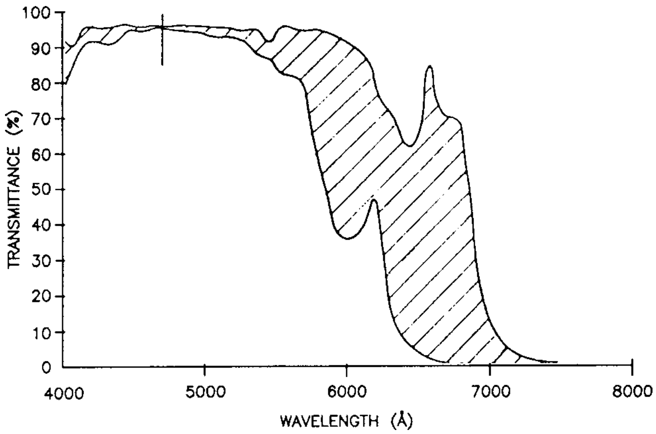

Fig. 3. Result as in Fig. 2 except where monitoring wavelength is in the middle of the passband.

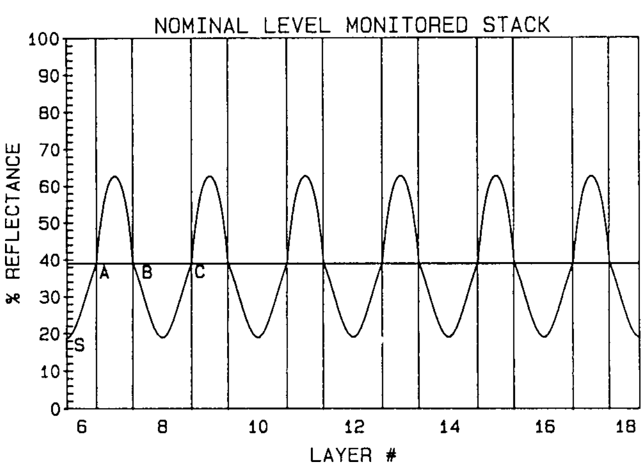

Fig. 4. Predicted optical monitor trace for constant level monitoring where each layer is terminated as its reflectance reaches the level as at points A, B, and C.

index of refraction of the layers being deposited and errors in the photometric scale of the monitor.

It is usually possible through appropriate test coating runs to characterize the index of refraction of the materials reasonably well. However, variations in rate, gas backgound, temperature, etc. can cause index variations. If these occur, the maxima and minima or turning values will be at somewhat different levels than those predicted by the design. This will disturb the stability of the level monitoring.

It is probable that errors of the photometric scale of the monitor cause even greater instability. The absolute transmittance or reflectance is not usually reported correctly by an optical monitor due to factors such as coating buildup on some of the monitor optics within the chamber, and due to drifts in the source and detector circuitry. This latter factor could be eliminated by the use of a true double beam optical monitor, but the former factor might be more difficult to overcome.

There are few absolutes (at this time) in optical thin film production; most processes rely heavily on calibration of most factors such as temperature, thickness, tooling factors, etc. In the case of the optical monitor, it would be highly advantageous to be able to calibrate the photometric level of the monitor just prior to the start of film deposition. If one is monitoring on a monitor chip, its reflectance/transmittance can be well characterized before loading it into the chamber. The monitor scale can then be calibrated by this reflectance/transmittance. If we monitor in reflectance with a bare crown glass monitor chip, the 4.2% reflectance is a poor calibration of where the real 100% scale point lies. In the case of transmittance monitoring, the 100% can be better calibrated. One calibration technique in reflectance monitoring that we employ, where the first layer is more than one quarter wave optical thickness of titania, is to use the peak (turning) value of the first layer of the stack. With titania, this is about 30% (depending on conditions and wavelength) and is therefore 7 or 8 times higher reflectance than bare crown glass. It should therefore be a correspondingly better calibration of the photometric scale.

STEERING CONCEPT

From a knowledge of the indices of the materials and the design of the thin film which has the desired period structure for level monitoring, one can calculate what the reflectance/transmittance maxima, minima, and cut points versus optical thickness should be. As a real deposition proceeds, it is unlikely that the values will appear to be just as calculated. It is possible to "steer" the subsequent monitoring trace to the desired values by small adjustments in the cut points from the nominal values based on the error observed at the most recent turning point. The proportion of the percent adjustment (short or long) in the nominal cut point to the percent error at the turning point can be calculated at the design phase of the monitoring plan. For example, as illustrated in Fig. 5, if a maximum were 4% too low (layer 11), the correction would be to cut the layer at 3% higher reflectance (point X) than nominal. If a minimum were too high by 2% (layer 14), the layer should be terminated 4% higher (point Y) than nominal. In principle, each correction has the power to bring the curve right back on track before the next turning point. This is because the correction is calculated to bring the cut point on the trace of admittance of the current layer to a point at the intersection of the admittance curve of the next layer which will bring it through the required turning value.

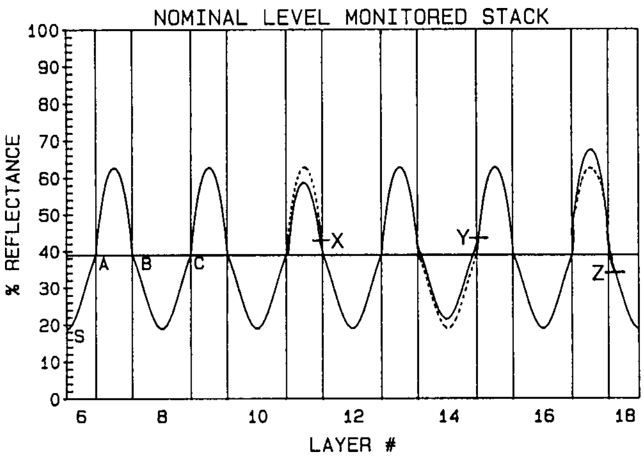

Fig. 5. Steering corrections (X, Y, & Z) for turning values that are too low (layer 11) or too high (layers 14 & 17).

This procedure is similar to steering an automobile down a road. If the driver finds himself off of the center of his lane due to wind forces, inattention, etc., he makes the necessary corrections to bring the vehicle back on track. Our operators have learned to steer the monitoring process to stay on the road and not crash into the ditch. Arriving at the final destination of the monitoring will reasonably assure that the monitored wavelength will have the designed spectral properties. The properties of the results further away from the monitoring wavelength will be determined by how near the center of the track the process stayed during the whole trip.

ALGORITHM

We will now describe the algorithm which has been shown in principle and in practice to overcome these problems and give good spectral results in the filter products with which it has been used. This algorithm has been recently implemented on an automated optical coating machine, but we have not yet had an opportunity to work with it extensively.

The algorithm has three sections which can be used or not as appropriate. The first section implements the basic "constant level" layer cutting scheme. The second section, which might be used instead of the first but not with it, makes it cut at a specified point which is a certain percentage or ratio of the distance between the last two extrema (max/min or min/max) of the monitoring curve. We will call the second section "general level" or "%MAX/MIN" monitoring. The third section is a correction factor to be applied to whichever of the first or second sections are used to account for the error sensed in the reflectance desired as the most recent turning point was past. This section has the power to correct for index variations, photometric errrors, previous cut errors, and to some extent many of the other possible errors mentioned above. This third section is the steering correction factor.

The equation or algorithm for the photometric level at which to cut the layer is as follows:

C(I) = J*(N*A(L)) "CONSTANT LEVEL CUT"

\+ (1-J)*(A(I)-F*(A(I)-A(I-1))) "GENERAL LEVEL CUT"

\+ K*(M*A(L)-A(I)) "STEERING CORRECTION"

C(I) is the photometric reflectance (or transmittance) at which the Ith layer is to be terminated and I is the layer number.

F,I,J,K,L,M, and N are parameters entered to describe in advance the layer properties desired for each layer, I. The A's are the actual reflectances of the last extrema (max or min) of given layer numbers.

J is used to turn on one or the other of constant or general level cut sections. When J=1, the constant level section is used. When J=0, the general level section is used.

L allows us to refer to the extremum (A) of some previous layer number L as a photometric reference or calibration. For example, if the first layer was titania deposited on a fresh crown glass substrate, we might know from experience and other calibration that the maximum was expected to be 31% reflectance for A(L). If we then wanted to make constant level cuts at 15.5%, the value of N for each layer (I) would be set at .5 (and J=1 and L=1).

If we had a general level cut as in Fig. 5 at the eighth layer (I=8) where the cut is 45.4% up from that last minimum of the distance between the last minimum and the previous maximum. Then: I=8, J=0, F=.454. This leads to C(8)=(1)*(A(8)-.454*(A(8)-A(7))).

When steering correction is to be used, K is not equal to zero (K<>0). The extremum of the current layer (as soon as it is past) is compared to the desired value M*A(L) which a factor M times a reference extremum as previously described. In Fig. 5, L=1, A(L)=31, and therefore M=2.032 for the high layers and .613 for the low layers. The factor for the constant level is N=1.258. The difference from the desired values or error is multiplied by the K for layer I and added to the cut level determined in section one or two of the algorithm. The K for a given layer is determined by separate analysis by the coating designer. It may be positive or negative and is usually of magnitude from 0 to 3. In the example of Fig. 5 with silica and titania layers, it is -2.0 and .75 respectively.

MORE ON PHOTOMETRICS

If the photometric scale is significantly in error, it may be difficult for the operator or automatic control system to steer to the expected values. A more or less stable result may be possible, but the edge will be shifted from the expected point. This might be compensated for by an appropriate shift in the monitoring wavelength in the next run, if everthing is otherwise reasonably reproducible. However, a more accurate photometric scale will produce more accurate results.

We discussed above the use of the bare monitored part and also the peak of the first layer for photometric calibration. There are at least two other approaches, that we know of, which may be of use for further development of photometric accuracy. From the design process, we know where the nominal cut point should be as a percent of the swing between the last two turning points. We also know the ratio of the nominal cut point reflectance to the maxima reflectances and the ratio of the minima reflectances to the maxima. For a given design, these ratios can be derived as a function of monitoring wavelength and layer thicknesses for given indices of refraction. This information can be used to determine in real time what the photometric scale really is, if the indices can be correctly assumed. The details of these schemes are beyond the scope of this paper, but our preliminary use of them has shown considerable promise.

RESULTS

Figure 6 shows the spectral scans of three successive production runs with the operators using using the steering algorithm described here. It can be seen that the edge position was controlled to +-2.5nm (0.4%) and that the passband in the region near the edge has relatively high transmittance. It should be noted that the substrate in each case is a heat absorbing glass whose uncoated transmittance is also plotted in Fig. 6.

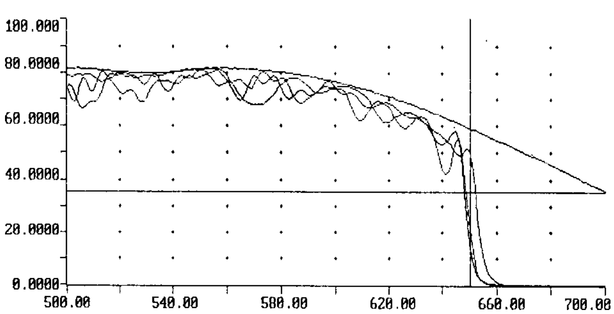

Fig. 6. Percent transmittance versus wavelength of three successive real production coating runs of over seventy layers where constant level optical monitoring with steering correction was used by the operator to make the layer terminations. The upper curve is the transmittance of an uncoated substrate.

CONCLUSIONS

The use of the steering technique in either constant level or general level cut optical monitoring leads to better control and more reproducible results in the edge position and passband transmittance of edge filters of the periodic structure type. It can be employed by operator monitoring and/or automated optical coating systems.

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