Simulation of Four Optical Monitoring Strategies

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ABSTRACT

The objective of this study has been to compare and quantify the simulated effects of noise, index errors, and photometric level errors on four different optical monitoring layer termination strategies. A computer program to simulate optical thin film monitoring has been written for this work. These four termination methods are: photometric cut level, two types of turning point termination, and percent change from the extrema of the last maximum and minimum in the optical monitoring curve (POEM). The turning point termination algorithms which have been implemented are described briefly. A 4-layer antireflection coating design has been simulated to find its possibilities and limitations, and to quantify the effects. The level cut strategy works well if the noise is low and the errors in index and photometric scale are small; however, systematic errors are a problem for level cuts in the presence of index and/or photometric scale errors. All of the other strategies are insensitive to index and/or photometric scale errors. It was found that two the turning point strategies work reasonably well from the turning point to points beyond that. The POEM strategy is robust and insensitive to errors when it is used beyond a ~5% difference from the photometric level of the turning point.

INTRODUCTION

An optical thin film monitoring computer program in FilmStar Basic[1] has been written to use in conjunction with the FilmStar Design[1] optical thin film software to simulate the effects of optical monitor signal noise, index errors, and photometric level errors on four optical monitoring layer termination strategies. The related use of simulation software by other groups[2,3] has been reported in the past. The new software has been written to allow testing of the POEM and a different TP algorithm that was not accessible in the previous simulation programs. The four termination methods evaluated here are: photometric level cut (LC), two turning point (TP) methods, and the POEM algorithm. The TP termination algorithms described also include the ability to terminate at a specified physical thickness (PT) **after** the TP has been found (TP+PT). Quartz crystal monitoring (QCM) errors have not otherwise been used in the present work.

It has been found that only the LC strategy is particularly vulnerable to index and photometric scale errors. The TP and TP+PT strategies are dependent upon finding the physical thickness at the TP by its **shape**, which is not affected by the index or photometric level. The POEM strategy is similarly unaffected because it works only with **percentages** between extrema which are not significantly altered by index and photometric errors. As a result, the LC strategy will not generally be used here because of its vulnerability. The emphasis is on the POEM and TP approaches in this study of single layers and a 4-layer broad band antireflection coating (BBAR), but it will be seen that the judicious use of QCM for thin layers and some other layers at certain monitoring wavelengths can also be expedient.

LEVEL CUT MONITORING

Level Cut (LC) monitoring is illustrated in first layer of Fig. 1. The layer is terminated when the optical monitor signal reaches a specified photometric level of reflectance (R) or transmittance (T). If the photometric signal is accurate and the index of refraction is as expected from the design, this approach can be satisfactory.

The POEM technique is also illustrated in Fig. 1. The second layer is terminated at 15.28% of the photometric distance between the last minimum and maximum down from the maximum. The third layer is cut 61.29% up, and the forth layer is cut at 10.04% up after the latest extremum.

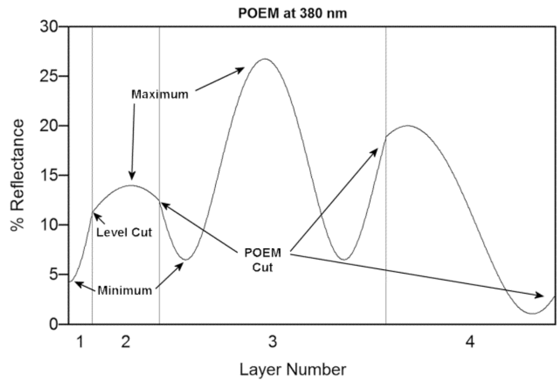

Fig. 1. A computer simulated monitoring curve of %R versus physical thickness monitoring at 380 nm in reflectance for the 4-later AR.

Figures 2 is an illustration with the optical monitor noise at ±0.2% and a 3% POE (Percent Of Excursion) between extrema in the mid-range of these studies. It shows the strong systematic errors in the PT of the termination due to index and photometric errors which could amount to as much as 5 or -10 nm when the index varies from 2.30 to 2.36 and the photometric scale is in error by ±1.0%. The standard deviation due to noise is small. However, when the % POE is small (3%), and the index is lower than expected (2.30), and photometric scale is compressed (99% in this case), and the expected termination level is above the level which would be reached by the monitor signal. In such a case, the termination **fails entirely**. Therefore, the LC approach is the only one of the four discussed here that is particularly sensitive to index and photometric errors, and would therefore tend to be less favored than the other three approaches.

Errors in the expected index of refraction and photometric scale translate into errors in the layer thickness when the Level Cut strategy is used. The effects are worse near turning points where the change in %R or %T are small with respect to thickness change.

The simulations reported below this section do not include index and photometric scale errors. When those were included, the TP+PT and POEM strategies showed no significant effects, as might be expected.

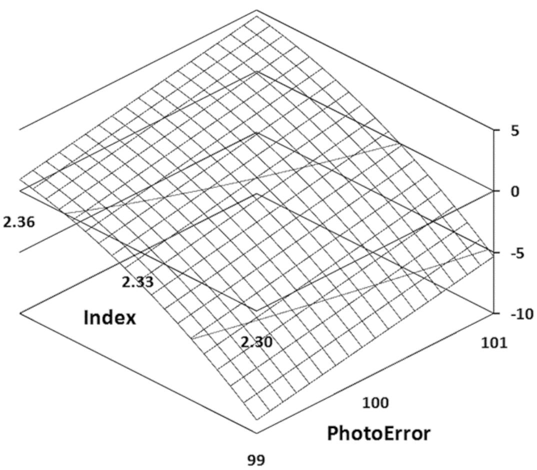

Fig. 2. Physical thickness error as a function of index of refraction variations and photometric scale error when using the LEVEL CUT strategy.

TURNING POINT MONITORING

There are several ways to find a TP when it occurs in an optical monitoring signal. Some of these methods have been described in the earlier paper[3]. The "Normal" mode mentioned there is similar to the 5-Point (5-pts) TP detector used here. The "Fitter" mode of Ref. 3 is related to what has been used in the present work and referred to as a parabolic fit (P-Fit). The 5-pts method indicates a TP when the last two points monitored show a change in direction from the first three points of the most recent five points in succession. The software of the Ref. 3 also includes the option to use 3, 5, 7, etc., points in the algorithm. The greater the noise, the more likely it is that a false TP will be found before the real TP is reached.

The "P-Fit" strategy fits the sampled monitor signal points to a parabola as new points are added, and it predicts where the TP will be in advance of actually reaching that TP. Figure 3 shows that a parabolic curve can be made to fit a sine curve in the region around a TP. The parabola is defined by $\mathbf{Y = a (X - b)^2 + c}$, where **a** defines the curvature at the vertex and **b** and **c** are the offsets of the vertex in the X and Y directions, as shown on Fig. 3. In the absence of

any noise in the data points, three data points in **X,Y** will define the **a, b,** and **c** of the parabola. The problem in this work has been to find the best estimate of the position of the TP on the X-axis in the presence of various amounts of noise in the optical monitoring signal (Y-axis).
In the presence of some noise, if three data points are taken in a close grouping at some great distance before the TP is reached, the predicted TP is likely to be greatly in error from that of the true TP position in X. If, on the other hand, the three points are widely spaced and cover a range in X which includes the TP, the prediction will be much more accurate. In the optical monitoring case, it is necessary that the points do not extend beyond the TP since the TP is to be found before or by the time that it is reached. However, it has been found that reasonable predictions for the position of the TP can be determined from data points before the TP with the P-Fit method.

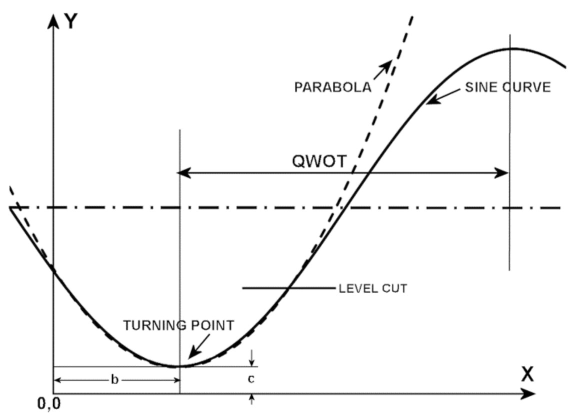

Fig. 3. A parabolic curve matches the sine curve in the region of a TP. The **b** and **c** constants define the position of the vertex of the parabola (TP) with respect to the origin. A Level Cut is also illustrated at a specified photometric level .

In these simulations, the interval between data points has been taken as 0.2 nm (2Å), which provides a few hundred data points per quarter wave optical thickness (QWOT) in the visible spectrum. For example, if a QWOT at 550 nm were being deposited at 4Å/ second, that layer would require approximately 2.5 minutes to deposit. This implies sampling at two samples per second which is well within the capabilities of current monitoring systems.

A typical raw optical monitor signal with ±0.3% noise is shown in Fig. 4. The inset in the figure is a 7X expansion with chart lines at 0.3% vertical intervals to illustrate the scope of the noise. This algorithm first **filters** the optical monitor signal with a moving average of 25 data points. This amount of filtering causes a phase delay of approximately 12.5 points with respect to when the TP is detected. If a 100 point moving average were used, the phase delay would be ~50 points.

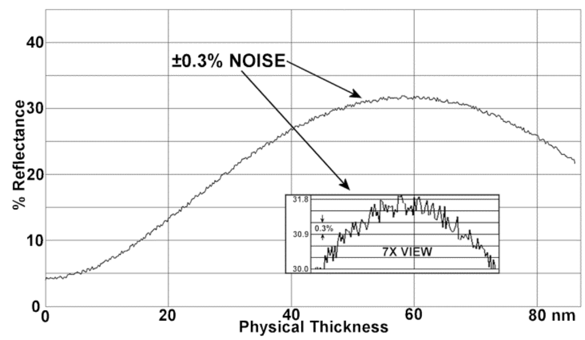

Fig. 4. A typical raw optical monitor signal with ±0.3% noise. The inset is a 7X expansion of the region around the TP with 0.3% vertical chart intervals to illustrate the scope of the noise.

The search for the TP in the filtered signal starts at 50 points in physical thickness (10 nm in this case) before the nominal PT where the TP is expected to be found on the basis of the design. The X,Y values of the next three points are used to calculate the predicted TP. This would be correct in the absence of noise, but probably would be highly in error in proportion to any noise. At the start, the "wheelbase" in X from the first to the third point is only two intervals of 0.2 nm. As new data points are added from the monitoring signal, the first X,Y point is kept the same, but the third point advances with each new point, and the second point used is the point half-way between the first and the most recent data point. Thus, the wheelbase and thereby the stability continues to increase with each new point, and the prediction becomes more accurate until the current PT equals the predicted thickness at the TP

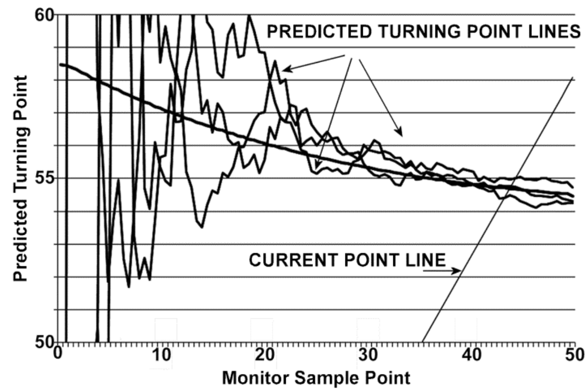

Fig. 5. Three different runs of the predicted TP with each new data point as it is calculated, with a monitor noise of ±0.1%. A line with zero noise is included.

(minus the phase factor of 12.5 in this case). Figure 5 shows three runs with a noise of ±0.1% full scale of the predicted TP with each new data point. This becomes more accurate with each new point. This algorithm is computationally fast as compared to a least squares fit of the data. A line with zero noise is included on the plot for reference, and a straight line also shows the X-value of the current point in the search process. When the current X point is equal to the predicted X point, the turning point has been found and the search is terminated.

Having found the TP as described above, its associated PT is known from the QCM reading. The addition to this approach which has been simulated here is to allow the termination of a layer some physical thickness beyond the TP by adding a specified PT; this is referred to as TP+PT monitoring. The PT in nm can easily be calculated from the design in preparation for the actual monitoring. Any error contribution in the PT from the QCM has been assumed to be negligible as compared to other errors in these cases. This extended approach can be applied to either of the P-Fit or the 5-pts termination methods after the TP is found.

TP monitoring is known to be accurate with respect to the optical thickness but not very precise. QCM is known to be precise but not very accurate, until it has been calibrated against a known optical thickness. The simulations performed in this study assume that the technique of Schroedter[4] has been implemented in the monitoring system. Schroedter recorded the optical monitoring signal levels (Y) at equal intervals indicated by the QCM (X) and calculated the predicted TP via a fitting algorithm. This minimizes the effects of deposition **rate** changes on the monitoring results. Historically, the monitor signal has typically been recorded as a function of time.

TERMINATION POINT SIMULATION

A single layer, monitored in R as seen in Fig. 4, was simulated to keep the first examples straightforward. The nominal layer was one QWOT at 550 nm of index 2.33 with additional thickness beyond the TP to allow terminations up to 15% of the excursion (4.26-31.64%R) down from the TP which was at 59.0 nm in PT. The noise was varied from 0 to ±0.3% of full scale; the index was varied from 2.30 to 2.36, and the photometric scale was multiplied from 0.99 to 1.01 times to simulate ±1.0% scale error. The distance of the termination as a percent of the excursion of the extrema was varied from 0 to 15%. The average PT error was evaluated in each case using 10 sample iterations with the specified random noise in the optical monitor signal (Y), and the average and the standard deviations (STDev) of those samples were calculated. Note that this work is all equally applicable in T.

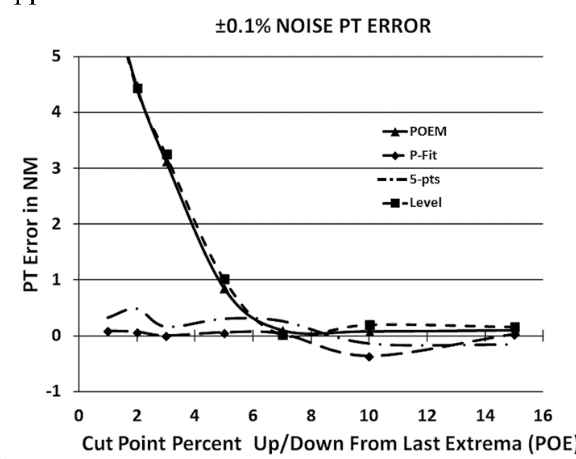

Fig. 6. Systematic physical thickness errors in nm versus cut point position (POE) with ±0.1% noise using the four different termination strategies.

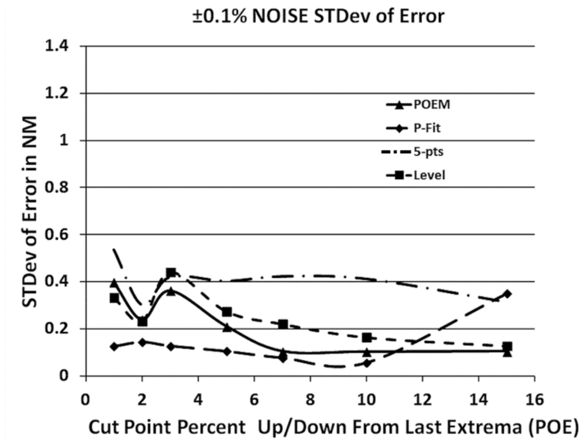

Fig. 7. Standard deviation of the PT error in nm from the data runs in Fig. 6 versus cut point position with ±0.1% noise.

Figures 6 through 9 show the results where the noise is simulated at ±0.1 and ±0.3%, but the index and photometric errors have been kept at zero. It can be seen in Fig. 6 with ±0.1% noise that the POEM and LC strategies have systematic errors at less than 7% POE. Figure 7 with ±0.1% noise shows that the STDev is reasonable for all approaches, but somewhat better at less than 10% POE for the P-Fit termination technique.

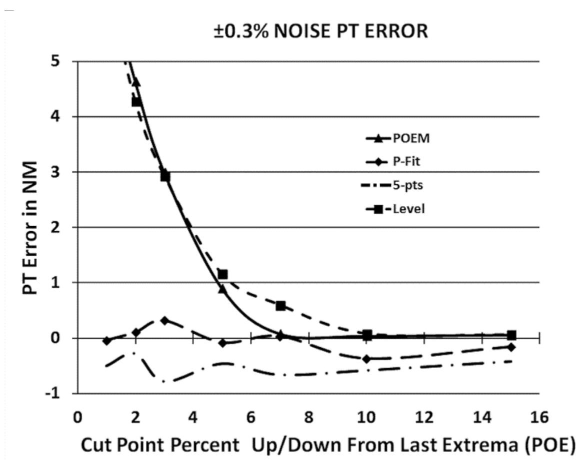

Fig. 8. Systematic physical thickness error in nm versus cut point position with ±0.3% noise.

Figures 8 and 9 show the effects of ±0.3% random noise on the systematic error and STDev of that error. The P-Fit strategy is the most

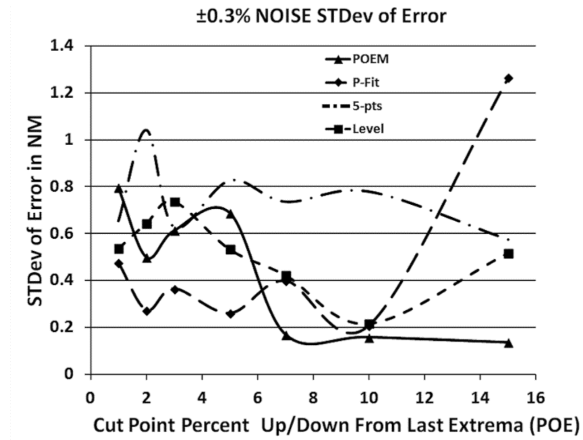

Fig. 9. Standard deviation of the PT error in nm from the data runs in Fig. 8 versus cut point position with ±0.3% noise.

accurate and precise for systematic errors for less than 10% POE and the POEM strategy is best from 7% POE through greater values. The STDev is not very precise for P-Fit at greater than 10% POE.

The general indications from the above is that the POEM strategy is preferred for greater than 7% POE. Either of the TP strategies is preferred when the POE is less than 7%, and the P-Fit is the least sensitive to noise of the two when the POE is less than 10%.

NOISE EFFECTS

The other dimension investigated with respect to these three monitoring strategies (excluding LC) is the effects of the amount of noise in the monitoring signal when using each of the strategies. The noise used in all of this work has been random values between plus and minus the particular percent of full scale given. If a nominal value at the TP were 31% (R or T) and the noise added were ±0.3% of full scale, the values of signal (Y) would be between 30.7% and 31.3%.

Two groups of simulations were performed with a constant 5% POE. The first group used a TP near 31%R (as in Fig. 4) for a QWOT layer (+PT) of index 2.33 on glass of index 1.52. The second group used a TP near 1.26%R for a QWOT layer (+PT) of index 1.38 on glass of index 1.52. For each case, 40 simulations were run, averaged, and the standard deviation (STDev) of the 40 runs computed at that particular noise level. The simulations were run from 0.0 to ±1.0% full scale noise in increments of 0.1%.

Figure 10 shows the results of the average thickness error versus noise at the termination in the first group for the three strategies, and also the design thickness of 69 nm is plotted as a dotted line. The POEM strategy works well, but P-Fit works even better than that. The 5-pts approach has increasing systematic error with increasing noise due to noise fluctuations before the TP being interpreted as the termination point.

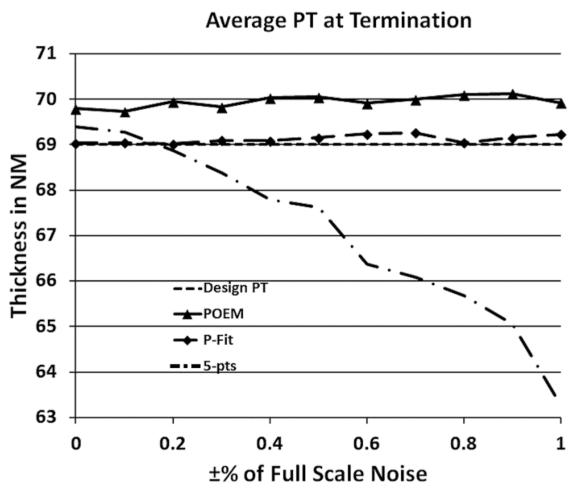

Fig. 10. Results of the average thickness error versus noise at the termination for the three strategies with 5% POE and a TP at ~31%R. The design thickness of 69 nm is plotted as a dotted line.

Figure 11 reports the STDev of the cases in Fig. 10. The P-Fit strategy gives the most reliable results, but all three are potentially usable.

The second group results illustrate the difficulty of an increased signal to noise ratio (SNR) in the optical monitor signal (of ~25 times less than that of the first group) from the 31% down to 1.26% at the TP. In Fig. 12, it is seen that only the P-Fit has small systematic error up to about ±0.3% noise, the 5-pts has strong systematic error, and the POEM failed entirely with any significant noise in the signal. Figure 13 shows the STDev of these two TP

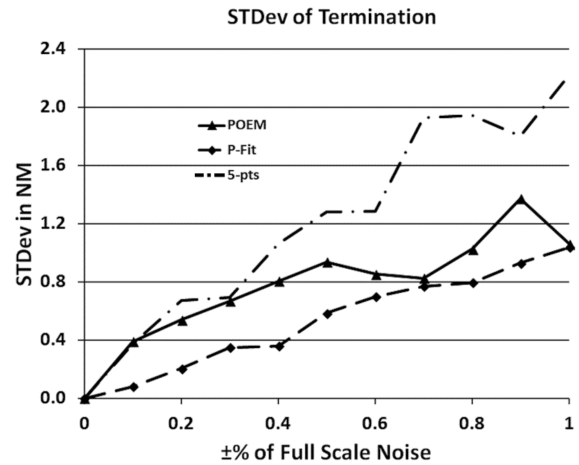

Fig. 11. STDev versus noise of the cases in Fig. 10.

termination strategies, and the 5-pts is quite a bit more stable. The thickness errors in Fig. 10 for the first group and Fig. 12 for the second group are both on the order of 1.5% of a QWOT. However the STDev is an order of magnitude less precise in the second group. These noise studies are consistent with the results in the previous sections.

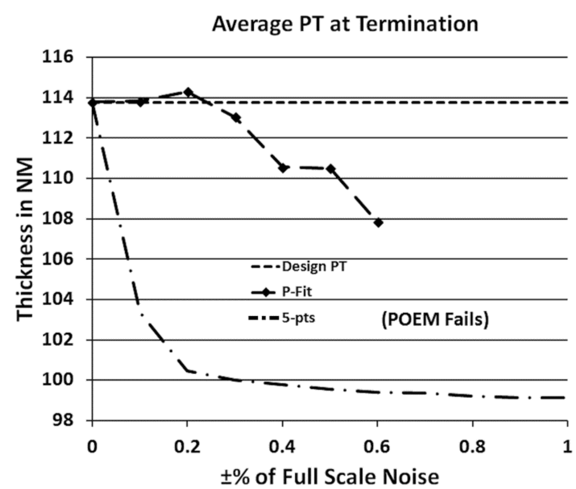

Fig. 12. Results of the average thickness error versus noise at the termination for the two TP strategies with 5% POE and a TP at 1.26%R. The POEM fails in this case. The design thickness of 113.74 nm is plotted as a dotted line.

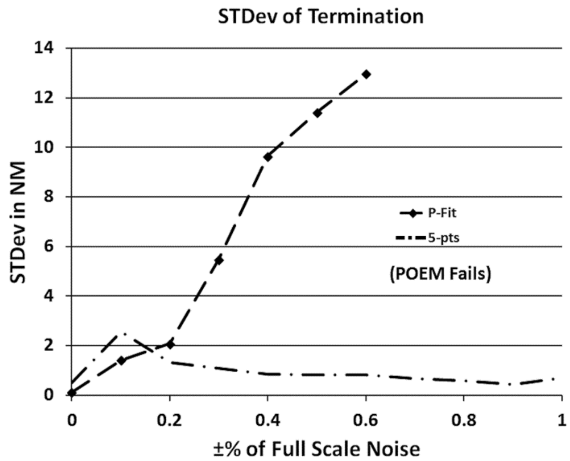

Fig. 13. STDev versus noise of the cases in Fig. 12.

In the report on another monitoring system[3], it was stated: "Experience seems to indicate that the typical real world photometric noise may be as little as 0.1%, it is usually less than 0.5%, and it rarely is worse than 0.9%." That paper was referring to peak to peak noise, whereas this paper is using ±X% noise, which is twice as large.

As a result, this paper would compare at 0.2, 1.0, and 1.8% respectively with the 0.1, 0.5 and 0.9% of the previous paper. The signal-to-noise ratios (SNR) will depend on the wavelength and %R/T of the monitor signal because of the light source power, optics transmittance, and detector response at that wavelength. One goal of work like that reported here is to select the monitoring wavelength which best serves the project at hand. Logic also points to the fact that monitoring all layers at the same wavelength, to the extent practical, allows the maximum benefit of the principle of monitoring error compensation at that wavelength, as is most often illustrated in narrow bandpass filters.

The 4-layer BBAR coating design used here has been optimized for the photopic response of the eye, and it has been studied by monitoring it at wavelengths from 380 to 830 nm in increments of 70 nm. The monitoring was done initially using **only** the POEM algorithm (and LC) at a single wavelength and on a single monitoring chip/piece in order to gain the maximum benefit of error compensations. It was found that this approach worked well when monitoring between 380 and 450 nm, but not well at longer wavelengths until between about 660 to 800nm was reached. The intermediate wavelengths are not practical with only POEM, primarily because one or more of the terminations are too near a TP. It will be shown that the use of TP monitoring for such layers (and QCM terminations in some cases) can make essentially the whole range from 380 to 800 nm practical for this design.

Figures 1 and 14 show the calculated monitoring curve for 380 nm where the terminations of layers 2, 3, and 4 are all well beyond turning points. In such cases, noise does not tend to cause a control break down (BD). The first layer is terminated at a level cut (LC) of a specific %R (plus the effects of noise) or by a QCM. In the simple LC termination, the termination levels of %R (or %T) are calculated on the basis of the calibration by the measured %R at the start point for the monitor glass of known index.

Figure 14 plots the simulated optical monitor signal for this 4-layer BBAR at each of the wavelengths studied from 380 to 800 nm. It can be seen that the 380 nm curve has frequent and large swings in reflectance with TPs that allow the POEM strategy to function well for layer 2, 3, and 4. At 800 nm, only Layer 3 has a TP before the termination, and thereby offers a good opportunity for a POEM termination of Layer 3. Other wavelengths have various intermediate situations.

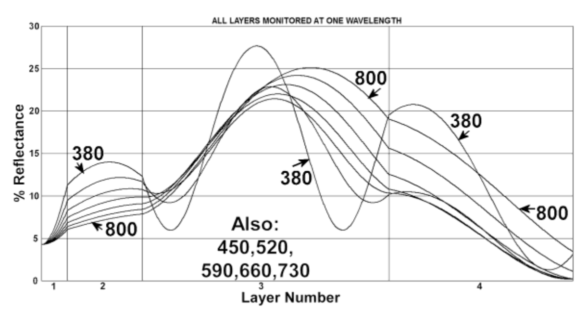

Fig. 14. Simulated optical monitor signal for this 4-layer BBAR at each of the wavelengths studied from 380 to 800 nm.

Figure 15 shows the results of ten runs each with random noise at the wavelengths from 380 to 800 nm, separated by 70 nm. For some percent of full scale noise at each monitoring wavelength, there is a point beyond which there is a BD where the monitoring does not yield any reliable version of the intended coating. This % is indicated at the right in the label on each simulation. These are the extreme cases for monitoring at each wavelength. Figure 16 also shows what would be representative for a noise level of 0.1% in **any** of these cases in Fig. 15. As shown in Fig. 15, 380 nm succeeds even in the presence of ±2.0% noise; 450 nm with over 0.8%; 660, 730,and 800 nm with up to 0.6, 0.8, and 0.7% respectively. The type of monitoring for each layer is indicated on each case in Fig. 15 by the codes such as 4111, 4413, etc. The code is: **1** for a POEM layer cut, **2** for a TP cut of the P-Fit type, **3** for a TP cut of the 5-pts type, and **4** for a QCM terminations.

Figure 15 shows the best results which could be obtained in this work by searching through the strategy options for each of the four layers at the given wavelength. In all cases for Layer 1, the QCM at 4% random error was less sensitive than optical monitoring in a LC. LC monitoring was not used in this work other than examining its use for Layer 1, because it was shown to be vulnerable to index and photometric scale errors. Except for the cases of this design at 380 and 450 nm, Layer 2 was found best by QCM, strategy 4. Layer 3 was best terminated by POEM in all cases except at 520 and 590 nm. The TP strategy of the P-Fit type works well for Layer 3 between 520 and 590 nm.

The use of the POEM termination in Layer 3 of this design seems to compensate well for any errors in layer thickness which occur before that point. This is evidenced by the fact that all of the monitoring results shown in Fig. 15 show little sensitivity to relatively high noise levels. The 380 nm example in Fig. 15 with **three** layers cut by POEM (i.e., 4111), shows the greatest tolerance for noise (2%).

RELATIVE MERITS OF FOUR STRATEGIES

Figures 17 and 18 illustrate the performance at 380 nm of the four termination strategies with ±0.3% full scale noise for 1) POEM, 2) TP via P-Fit, 3) TP using 5-pts, and4) QCM with 4% random errors. The QCM is the only one of these strategies which has no potential for error compensation, but it has the advantage of being simpler and less expensive hardware. The 4% noise chosen here to illustrate the QCM may be more severe than that achieved by some facilities using proper care.

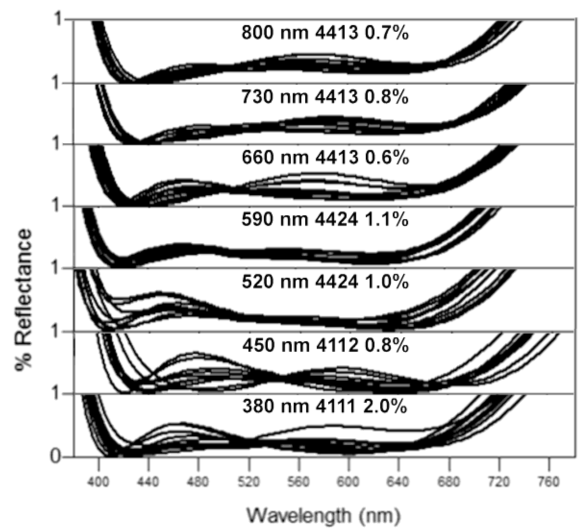

Fig. 15. Results of ten runs each with random noise at the wavelengths from 380 to 800 nm showing the strategies for each layer (i.e., 4112) and the % noise before a BD on the right.

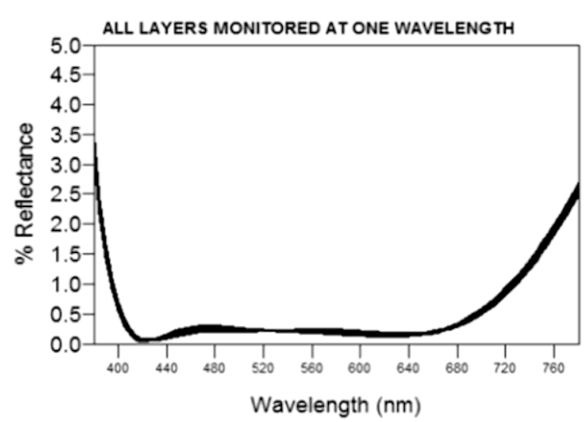

Fig. 16. Results of ten runs each with random noise at the wavelengths from 380 nm with the strategy for each layer of 4333 and the noise percentage of ±0.1. The other strategies and wavelengths shown in Fig. 15 look essentially the same at this noise level

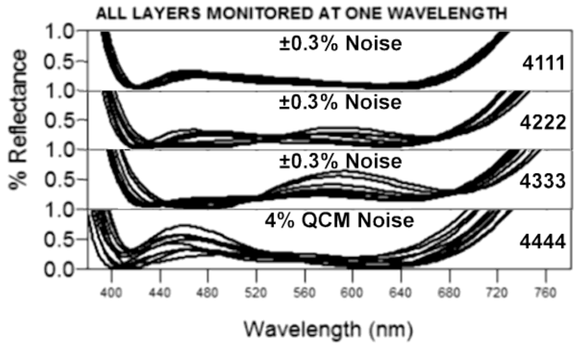

Fig. 17. Performance at 380 nm of the four termination strategies with ±0.3% full scale noise for POEM (4111), TP via P-Fit (4222), TP using 5-pts (4333), and QCM (4444) with 4% random errors.

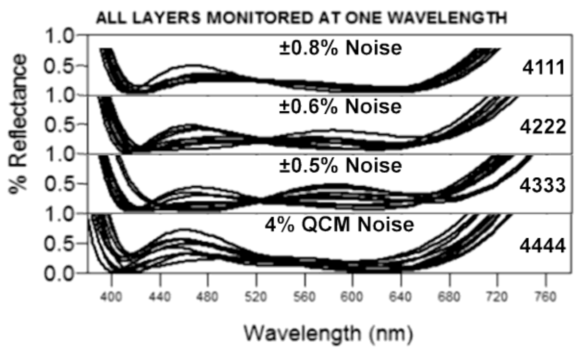

Fig. 18. Same as Fig. 17 except with ±0.5% full scale noise; the ranking is the same.

Layer 1 is always a QCM cut in these cases and all of the other layers are of the same type within each example, such as 4111. It can be seen that the results are best for the POEM and that the TP strategies slightly worse for P-Fit and then 5-pts. Figure 18 is similar to Fig. 17 except at ±0.5% noise, and it shows the same relative ranking in performance.

CONCLUSIONS

The task of this work was to choose a monitoring wavelength and strategy from these various options which gives the best results under the circumstances at hand. The POEM strategy is shown to be the most robust when it can be used from 5% POE to all higher values. The two TP strategies can be employed if necessary, and the QCM can be used as needed, but QCM contributes nothing to error compensation. The two different TP+PT strategies are shown to be good choices for terminations that are 10% POE or less. The P-Fit has less systematic error at both low and higher SNR, but the "5-pts" has better stability when the SNR is low.

The photometric Level termination strategy suffers from sensitivity to index and photometric errors, but the other three strategies are essentially insensitive to these errors.

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