Analysis of Optical Monitoring Strategies for Narrow Bandpass Filters by Software Simulation

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ABSTRACT

Narrow bandpass filters have historically been optically monitored at the central wavelength of the passband on a deliverable substrate by terminating each layer at a turning point. This has been shown to have error compensating effects which make possible resulting performance which could not otherwise be achieved. Another strategy has been proposed wherein the ratio of the thickness of the high and low index layers of each layer pair, which normally total one half-wave of optical thickness, is changed from 1:1 to a somewhat different ratio while maintaining the one half-wave total layer pair thickness. The spectral details of the modified design differ little from the classic design; those differences are in proportion to the difference of the ratio from the usual 1:1. This can create a situation where there are two turning points within one of the layers and none in the other layer of the pair, and the layer terminations are suitably placed just after turning points. These termination conditions provide an opportunity for greater accuracy and reproducibility in the layer thicknesses. The simulation capabilities of optical monitor software have been used to compare the results of this strategy with that of the classical turning point method in the presence of random noise in the optical and crystal signals.

Keywords: Optical coatings, optical monitoring, simulation

INTRODUCTION

We previously reported on the simulation of errors in the monitoring of narrow bandpass (NBP) filters[1,2] and introduced the FencePost (FP) design[3] and monitoring[4] concepts. This FP approach has also been applied as an aid to atomic layer deposition (ALD) work[5]. A report[6] on more detail on the FP work lead to the use of a different computer simulation program by-and-with Alfons Zoeller[7,8] to further verify the concepts.

Yet another computer simulation program, FilmMaker[9] (FM), has now been applied in this present work to further assess the behavior of the FP (non-turning point (TP)) monitoring techniques. The goal of this work has been to use this simulator capability to compare the performance of the proposed FP monitoring concept with the classical TP approach on NBP filters.

Figure 1 shows the optical monitoring (OM) plan using TP layer terminations (cuts) in the classical way for a fourteen layer (14) NBP filter. Figure 2 shows the monitoring plan for a similar design using the FP concept, wherein the layer terminations are well beyond the TPs.

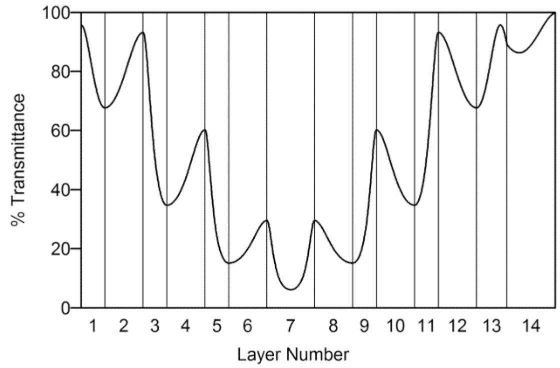

Fig. 1. Normal 2:1 NBP optical monitoring plan using TP layer terminations in the classical way for a fourteen layer (14) NBP filter.

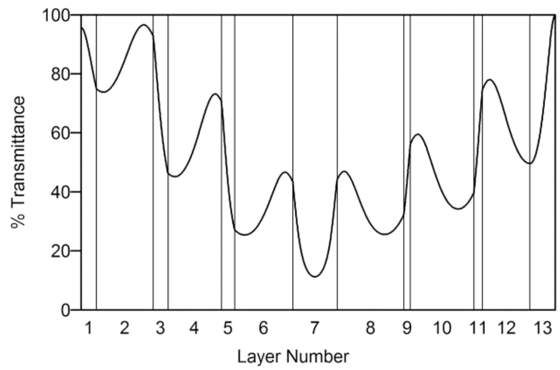

Fig. 2. Monitoring plan for a similar design to Fig. 1 using the FP concept, wherein the layer terminations have been adjusted to be well beyond the TPs.

Figure 3 compares the spectra of the two designs in Figs. 1 and 2, where the classical design has a somewhat narrower passband and more optical density (OD) in the blocking bands. However, the differences can mostly be overcome by redesigning the FP with a few more layers. The overall blocking band is somewhat narrower for the FP, and this is not so easily adjusted; but the normally required blocking filters can overcome this problem.

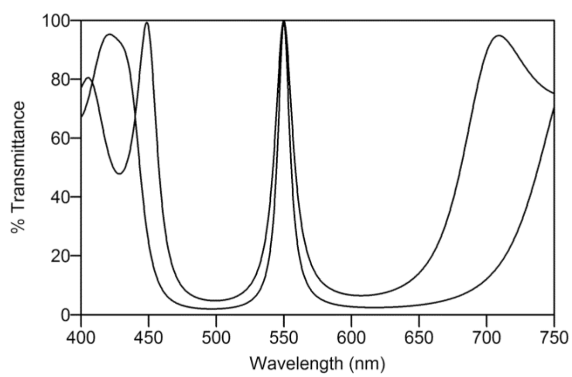

Fig. 3. Comparison of the spectral performance of Figs. 1 and 2; the Fig. 1 curve is generally lower in this figure.

The FilmMaker software has three Analyzer Modes to find a TP that have been used in this work: Normal, Fitter, and Crossing. The Normal Mode finds the TP based on where the filtered signal curve changes direction. The Fitter Mode finds the TP by fitting a parabolic function to a moving window of a selected width over the latest signal data points, and this mode can thereby predict where the TP will occur. The Crossing Mode finds the TP where the base filtered signal crosses with a signal of slightly different phase delay. We found the results of each of these are generally similar, when using very high noise levels and we have primarily used the Normal Mode. In future work, it might be advisable to use the Fitter Mode where much less filtering of the signal would be used and thereby negligible phase delay would be incurred. The result of each of these modes is to determine where the TPs have occurred, which is the basic frame of reference for this type of optical monitoring. Cuts can be made at TPs or some fraction of a quarter wave optical thickness (QWOT) thereafter. When there is a cut after a TP, the termination is determined by the photometric (vertical) signal difference from the level of the last TP. In the case of the raw signal with no filtering, the sensitivity and precision of such a cut depends in principle on the slope of the photometric change with layer thickness; and this will be greater with increasing distance beyond the TP, up to 0.5 QWOT beyond the TP. This is the motivation for these non-TP or non-QW cuts, to get greater precision than a TP cut; and this leads to the FP concept. However, this principle can be disturbed if there are variations in the index of refraction from what is expected and/or variations in the deposition rate. In such cases, terminations closer to the TP would be less influenced by these anomalies. Filtering of the raw photometric (optical) signal can be adjusted from very weak to very strong filtering. The present work has been done with very strong filtering to cope with the artificially high noise levels (i.e., 8%) which have been used here to make the effects more apparent. When only realistic levels such as 0.1-0.2% noise are to be considered, much less filtering could be used, phase delays would be much less, and the FP principle of seeking a steeper slope would again be more applicable. However, effects of index and rate might still favor terminations chosen toward the shorter distances from the TPs to minimize the impact of those anomalies.

Cuts by crystal thickness are implemented in FM by "Cut Using Time". The FP concept also includes the concept that crystal terminations can be used to advantage for thin layers, and their errors can be well compensated in following optically cut layers. The FP approach is to use crystal cuts for every other layer (which are the thinner layers) and cut the thick layers in between these optically because they have two TPs in those layers. Also the last two AR layers of these NBP filters are cut by crystal because of our findings reported earlier in the literature[10].

The use of crystal terminations has be adhered to in this current work to be consistent with the earlier proposal for FP monitoring. However, in the case of automated optical monitors such as those by Intellemetrics, it is also possible to terminate the intervening layers (which were cut by crystal as mentioned above) by TP monitoring by changing the monitoring wavelength for these layers so that a TP may be achieved in each of them. Since the automated monitor can quickly and accurately return to the original monitoring wavelength, i.e. the wavelength of the NBF, the maximum error compensation is preserved; and it is likely that the terminations of the intervening layers will be more accurate and stable than the crystal terminations.

The simulation program can randomly vary the noise in many parameters. The noise sources used for simulation here were the percent of full scale signal noise in both the high and low index materials and the percent error in the crystal thicknesses.

To gain the maximum benefit of error compensation, all of these simulations were done at a single monitoring wavelength on a single monitor glass using crystal cuts only where they were found to be more stable than optical cuts, and also in the case of the last two layers[10].

It has also been found that crystal cuts can be used advantageously where a TP is difficult to find accurately, such as the layer just after a spacer or cavity layer in a NBP filter. In fact, it was found that the best results were obtained with the "classical" TP cut mode when the crystal cut approach was used on the 1st, 3rd, and 5th layer after the spacer layer because the shape at the TP where the cut is desired is quite flat, i.e. there is a small change in photometric level with layer thickness. The above comments on the automated optical monitor might also apply to the last two layers and these troublesome layers.

The normal NBP design used in this study was (1H 1L)3 2H (1L 1H)3 .282H 1.263L, where H is 2.35 and L is 1.46. and the substrate is of index 1.52. This is referred to here as a 2:1 design because that is the ratio of the overall thickness of the layer pair (1H 1L) to that of the thinnest layer in the pair. The starting 3:1 (FP) design used here was (.667H 1.333L)3 1.745H (1.333L .667H)3 .339H 1.265, for example. The resulting adjusted design of Figs. 2, 3, and 7 was: .607H 1.4016L .59626H 1.31772L .53458H 1.43642L 1.77078H 1.65273L .25807H 1.56618L .35123H 1.1762L 1.00429H. The 14th layer became superfluous in this particular case.

In this study, we simulated designs with ratios of 2.0, 2.5, 2.75, 3.0, and 3.5. The random optical signal noise producing photometric errors were varied from 0% to over 3%, and the errors in crystal cuts from 0% to over 10%. 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%. Similarly crystal errors may be as little as 1%, it is usually less than 4%, and it rarely is worse than 6%. In order to **accentuate the comparisons**, we have used 8% photometric errors and 1% crystal errors for Figs. 4 and 7, but normal errors are expected to be **much** less than these values.

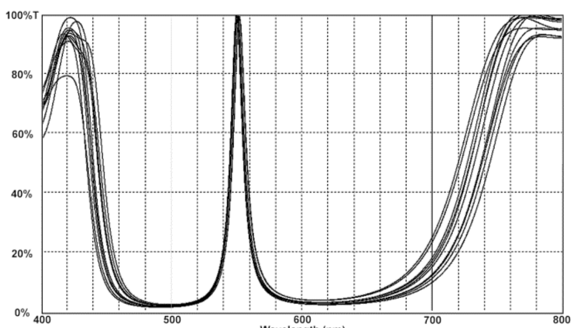

Fig. 4. Normal 2:1 NBP filter design of Fig. 1 with 8% random signal noise and 1% random crystal errors.

It can be seen that the passband at the monitoring wavelength is **very** stable, and errors only appear on the other side of the blocking bands. The usual additional blocking filters would cover any of these imperfections. The results for the Modes of Normal, Fitter, and Crossing all look the same to within the random fluctuations in the spectral curves.

Figure 5 shows the results of this design with all layers terminated by crystal cuts, where the random errors are 5% and there can be **no error compensation,** for comparison with Fig. 4. The difference between Figs. 4 and 5 illustrates the benefits of error compensation. The errors in Fig. 4 are greater than those in Fig. 5, but the use of optical monitoring on at least every other layer compensates for those errors at the monitoring wavelength.

The error levels were surveyed to find the limits where they would cause a process to have less than 100% yield, because this would cause the loss of a total production run. Within these limits there would only be loss of spectral shape with respect to the designed spectral curve. All of the Modes were found quite tolerant for the classical 2:1 design cut at TPs even at the 8% case for optical errors and 1% crystal errors illustrated in Fig. 4. Many simulations were run to find the 100% yield limits for the FP approach as a function of optical and crystal noise/errors. Figure 6 summarizes the findings. Using 4% random crystal errors, the 100% yield limit (statistically) was found for various Layer Pair Ratios. As can be seen in Fig. 6, if the optical noise was 0.5% or less, a ratio of 2.75:1 could be used, but if the optical noise were 2%, the ratio would need to be 3.5:1 or greater. It can be seen that even if the optical noise approached 0%, the ratio would need to be greater than 2.5:1 to have a 100% yield.

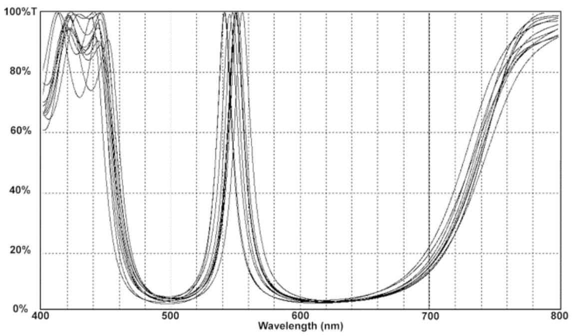

Fig. 5. Normal 2:0 NBP filter with all layers crystal cut and 5% random crystal errors and no error compensation.

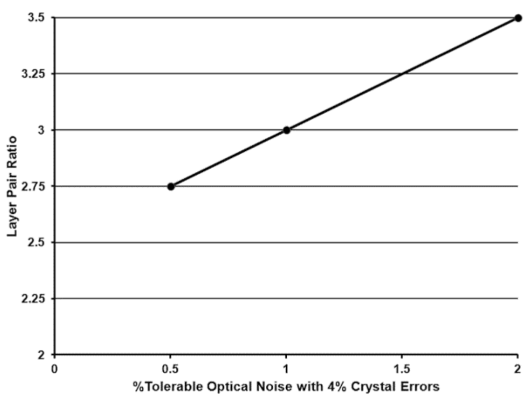

Fig. 6. Minimum layer pair ratio in the FP method for 100% yield versus optical noise with 4% random crystal errors.

The optical noise level was taken to the extreme of 8% to show the difference in performance of the approaches in Figs. 1 and 2. Designs with 8% optical noise and 1% crystal noise were simulated and are shown in Fig. 7 for comparison with Fig. 4. The passband is slightly broader due the nature of the FP effects but could be further adjusted by adding lair-pairs as needed. The control in the passband is still good and the out-of-band noise is significantly reduced by the FP approach.

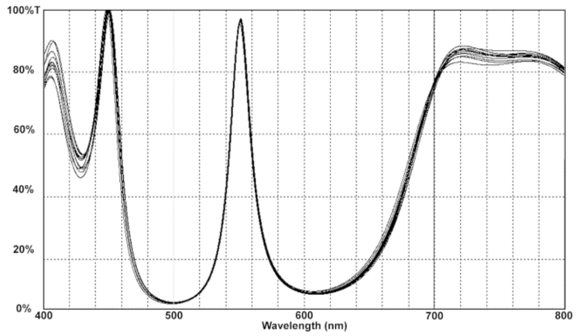

Fig. 7. Design from Fig. 2 to compare with Fig. 4 with 8% random signal noise and 1% random crystal errors.

This work has also allowed the estimation of the effects of the distance from a TP needed for a termination in the presence of various amounts of optical and crystal noise. Over a thousand simulation cases were run with various designs in the presence of various amounts and kinds of random noise. When these results were processed with the statistical methods of design of experiments (DOE) methodology, etc., two major characteristic behaviors were observed and confirmed. One, the size of the error in layer thickness termination is linearly proportional to the amount of noise in the optical signal, whether in the classical TP of FP mode. Two, the sensitivity to optical noise error is inversely proportion to the slope of the transmittance (T) with layer thickness in the FP mode. Since the shape of the %T curve around a TP is nearly sinusoidal or parabolic with the %T proportional to the square of the distance from the TP, the derivative of %T with respect to layer thickness is linear with distance from the TP.

Figure 8 summarizes these results for the cases of layers 2 and 8 as in Fig. 2. Here the signal level is higher at the termination of layer 2 than layer 8, and therefore the signal to noise ratio is better. This figure shows the % of layer thickness error to be expected as a function of the %T difference at the cut point from the %T at the TP. For example, when the cut %T is 0.6% down from the TP in layer 2 with 1% noise in the %T signal, the layer thickness error will be ~0.2%. On the other hand, at layer 8, the same difference of 0.6% up would cause a layer thickness error of ~0.56%. The four dots on the curves in Fig. 8 show where the **classical TP cuts** would be for the same layers and noise values. Therefore, one must chose to operate at a %T Difference to the right of those dots to gain any advantage from using the FP concept versus the classical TP method.

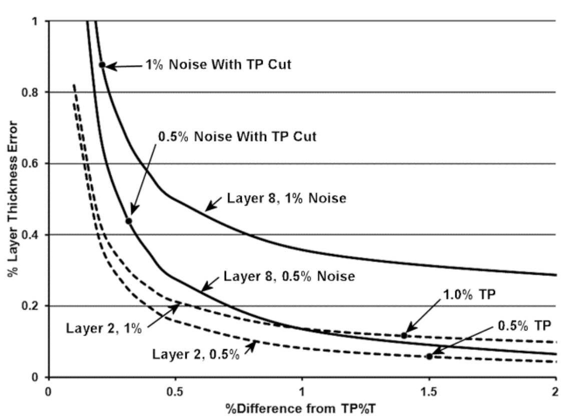

Fig. 8. Summary of the results for the cases of layers 2 and 8 as in Fig. 2.

The layer thicknesses in the case shown in Fig. 2 (and 3) were manually edited to give the same slope at the termination of layers 2, 4, 6, 8, 10, and 12, so that they would all have the same reduced sensitivity to noise errors. These layers were also edited to have the first TP in each layer at the same physical thickness from the start of that layer. It is planned that this editing process will be described in a future paper.

The noise in the optical monitor signal has been highly exaggerated in the above cases to make the effects apparent and able to be compared. Here a more realistic case will be shown. Figure 9 illustrates the excellent performance which can typically be achieved at a normal optical termination noise level of 0.2% or less. This figure is to be compared with the left part of Fig. 7 where the noise level was exaggerated to 8% for comparison with Figs. 4 and 5. In Fig. 9, it is difficult see any influence of the typical noise level even at the short wavelength end where the effects should be the strongest (as in Fig. 7).

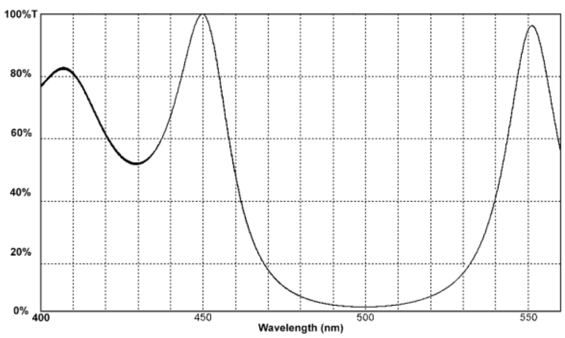

Fig. 9. Design from Fig. 2 with ten (10) iterations using a realistic 0.2% random optical monitor signal noise to compare with the left part of Fig. 7. This is ten independent traces which are so close as to look almost like one trace.

CONCLUSIONS

The error compensation effects of single wavelength and single chip monitoring have again been shown to be **very** strong, and the FilmMaker software is well suited to implement this classical TP monitoring. The tolerance to noise in the optical monitor signal can be made surprisingly high, up to orders of magnitude more than the noise which might reasonably be expected to exist in a real optical monitor system.

It was shown by simulation that the effects of optical monitor noise on film thickness errors are linear, and the error sensitivity to noise decreases linearly with distance of the layer termination beyond the turning point. Also, an indication of the minimum distance beyond a turning point which is needed to achieve better results from non-turning point terminations than from the classical turning point terminations has been given.

The passband width and blocking depth of a FencePost design can be adjusted to match the non-FencePost design by adding layers and reoptimizing. The starting and ending slopes and positions of the optically monitored layers can also be adjusted over some range while still preserving the essential spectral features of the design.

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