Preserving Error Compensation Benefits While Changing Monitoring Wavelengths With Each Layer

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ABSTRACT

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Error compensation in optical monitoring has been known for decades as being the saving grace that allows high-performance narrow bandpass filters to be produced at all. The key to that success has seemed to be direct monitoring of the deliverable part, or as close to that as possible, at the wavelength to be delivered. These principles using single wavelength monitoring on a single glass/chip have been extended to more general coating designs such as antireflection coatings, etc., in order to gain the compensation benefits. The current work shows by simulation that the monitoring wavelength can also be beneficially changed for up to every layer in the design without loss of the compensation effects. Direct monitoring on a single deliverable part, or at least a single monitor glass/chip, is still required for maximum error compensation. However, as long as the monitoring wavelength can be changed reproducibly, the described scheme of changing wavelengths to terminate at points which are more sensitive than "turning points" should provide improved control and repeatability of the spectral results. Simulations under various noise-in-the-signal conditions are provided.

INTRODUCTION

Narrow bandpass (NBP) interference filters prior to the early 1950's were made of a dielectric spacer of about one half wavelength optical thickness (HWOT) at the passband wavelength between two partially transmitting silver layers as mirrors. This was classically referred to as a form of the Fabry-Perot Interferometer. Polster[1] introduced the concept of replacing the silver mirrors with all-dielectric mirror stacks which had essentially no absorption and whose reflection could therefore be designed to have much higher reflection and give narrower bandwidths. The practice to produce such filters was to deposit alternating high and low index layers of quarter wave optical thickness (QWOT) to produce the mirrors and separate them by a spacer of one or more half wave optical thickness (HWOT) at the passband wavelength. Figure 1 shows what such a monitoring trace might look like at the designed passband wavelength (such as 550 nm), and Figure 2 shows how the spectral transmittance plot would appear.

The only way used to control the layer thickness at the time of Polster was to observe the transmittance of the depositing layers at the monitoring wavelength of the passband to be produced, and to terminate each QWOT at the turning point (TP) of the monitoring trace. The ability of the observer to cut the deposition at the exact TP might be limited to only ±5% of QWOT. Figure 3 shows the results of such random ±3% uncompensated errors, also such as might be obtained by crystal monitoring, on the filter performance. This is clearly not an acceptable result. The actual results, however, were much more successful than that shown in

Figure 3. Macleod[2] discovered why the practice was successful: it was "error compensation." His comment was: "The results of the first computer runs were very surprising. Turning value monitoring gave the enormous thickness errors which were expected, but the computed performance of the filters was found still to be satisfactory."

Figure 1 shows the typical optical monitor trace for the deposition. As the first layer (H) is deposited, the transmittance drops to point A. The next QWOT of L raises the transmittance to point B, etc. This continues to the symmetric center point of the thin film stack in the HH (HWOT) spacer layer for this filter. The transmittance then increases symmetrically as the later layers are deposited. The last layer restores the transmittance of the ideal filter to the original starting value which the substrate had (at the monitoring wavelength).

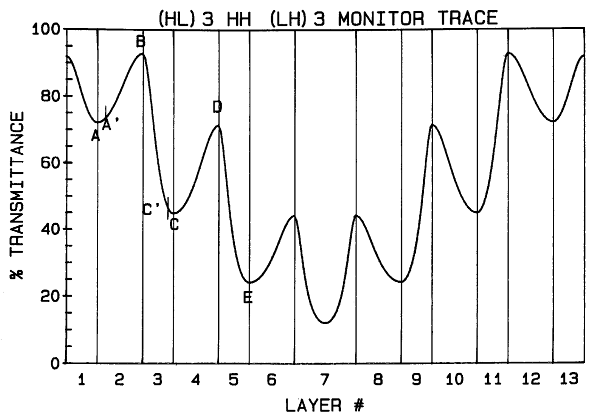

Figure 1. Optical monitor trace of a 13-layer NBP filter at 550 nm as in Figure 2. The ideal layer terminations are at A, B, C, D, E, etc., while errors are shown at A' and C' which are partially compensated by terminating the next layer at the next turning point.

Let us imagine that the first layer in Figure 1 was terminated in error at A' instead of at A. The second layer would still be cut as close to the turning point B as possible. This means that the second layer will be shorter than the design by just enough to make up for the error in the first layer and produce two full QWOT's for the pair of layers. Similarly, if the third layer stopped short at C' instead of C, the fourth layer would just make up for the loss if stopped at the turning point D. Figure 4 shows the effects of random 3% of a QWOT RMS errors where the natural compensation of attempting to cut at all the turning points was in effect.

The benefit of this compensation is obvious when Figs. 3 and 4 are compared. Macleod[2] performed an extensive analysis of the technique and the effects of errors. Bousquet, et al.[3] discuss this type of compensation in some detail. The keys to the effectiveness of this compensation are that the monitoring wavelength is right where we are most interested in the performance, the monitor is looking through the actual substrate to be coated (direct monitoring), and the monitor sees all of the effects of all of the layers deposited from start to finish. If any of these elements are missing, this degree of error compensation cannot be expected.

It can be seen in Fig. 4 that the performance of the error compensated NBP away from the monitored wavelength departs with increasing wavelength progressively further from the design without aberration. In a typical NBP design, the side bands where the filter starts to transmit again are blocked by additional edge filters on the long- and short-wavelength sides. These edges will have to be slightly closer here to the central peak of the NBP than indicated by the ideal design in order to allow for the effects of the errors, even though they are well compensated at the central wavelength.

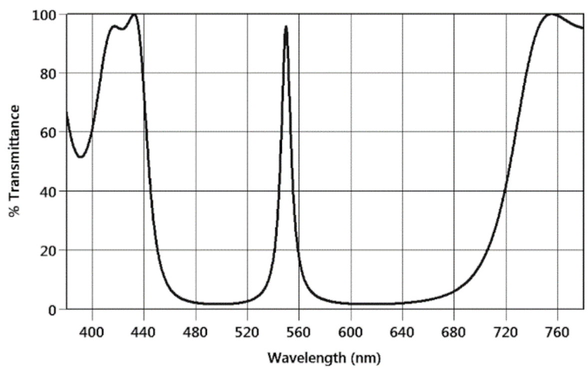

Figure 2. Spectral plot of the 13-layer NBP filter of Figure 1.

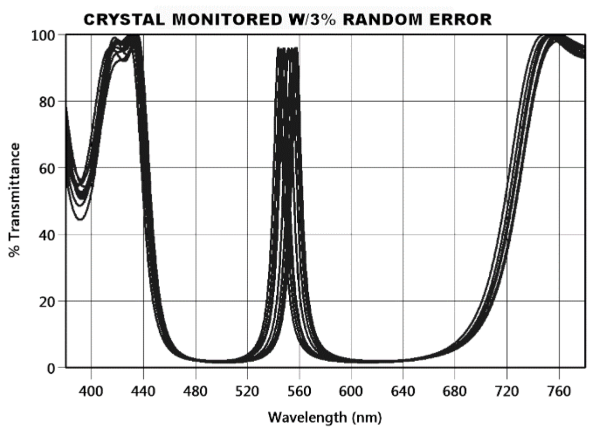

Figure 3. Spectral plot of 10 cases of the filter in Figure 1 and 2 with random ±3% uncompensated errors in each layer.

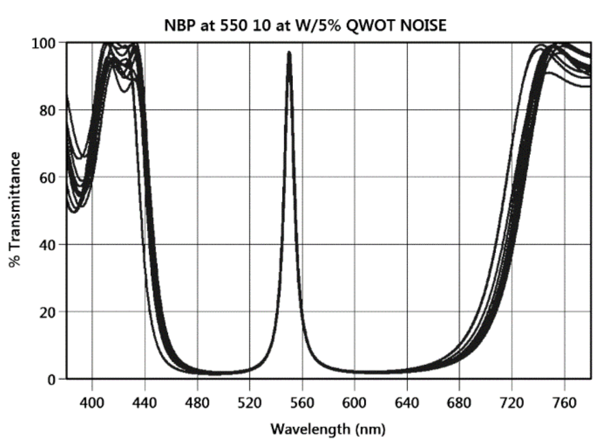

Figure 4. Spectral plot of 10 cases of the filter in Figure 1 and 2 with random ±5% QWOT errors in each layer, but where "turning point" monitoring was used giving error compensation.

The author previously thought that the compensation benefits discussed above might be lost if the monitoring wavelength were changed from layer-to-layer or was not at the central wavelength of the NBP filter. However, upon further thought and simulation, that limitation is withdrawn and wavelength change from layer-to-layer is perhaps even encouraged.

PERCENT OPTICAL EXCURSION MONITORING

The Percent Optical Excursion Monitoring (POEM) technique has been described variously by the author[4-9]. The present paper applies that technique combined with the changing of wavelengths with each layer to obtain near optimal results in optical thin film reproducibility in the presence of noise in the monitoring signal. Figure 11 and 12 in Ref. 9 showed that terminating a layer past a turning point (TP) where the POE was 10% gave better results than 5%, but that 15% was not much better than 10%. Terminating a layer at a POE of 50% would provide the greatest percent change of transmittance or reflectance with change of thickness. A 10% POE provides about 0.59 of that maximum rate, while 5% and 15% provide 0.32 and 0.82 respectively. A POE of 10% was selected with a thought to balance the 'staying close to the TP' but also 'the staying close to a steep slope' to minimize the effects of noise.

Software was written in the Basic language of FilmStar[10] it implement the POEM strategy simulations used in the present work.

Figure 5 shows an optical monitor trace at 529.8 nm of layer #7 in the NBP filter design of Figs. 1 and 2. Here the layer termination is to be at the point indicated as 10% POEM which is 10% of the transmittance excursion between the minimum and maximum TPs downward from the last TP (the maximum transmittance).

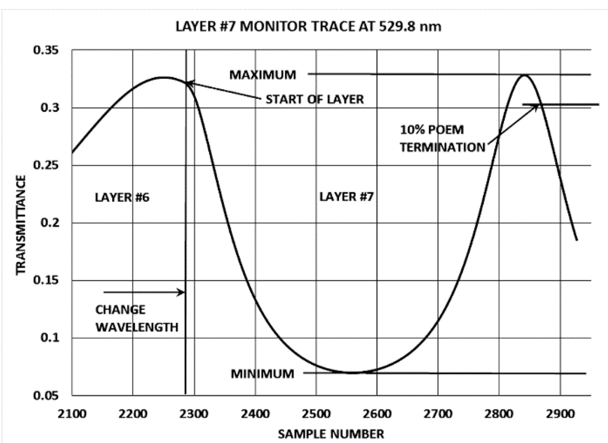

Figure 5. Optical monitor trace at 529.8 nm of layer #7 in the filter design of Figs. 1 and 2.

In contrast to the case in Fig. 5, Fig. 6 shows layer #2 where the maximum to be used in the calculation for a 10% POEM is the start of the layer #2, **not** the maximum in the previous layer, #1. The reason for this is that the wavelength has changed from layer #1 at 427 nm to layer #2 at 482 nm; therefore, the only useful information for layer #2 starts at the beginning transmittance of layer #2 after the wavelength is changed.

In the results reported below, each of the 13 layers in the design of Figs. 1 and 2 were monitored at a wavelength to terminate at a POE of 10% and random noise was applied to the monitor signal as in Ref. 8.

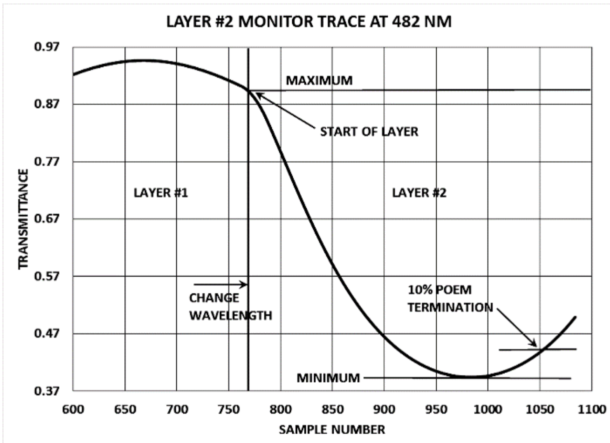

Figure 6. Optical monitor trace at 482 nm of layer #2 in the filter design of Figs. 1 and 2.

In discussions with the coauthors of Refs. 7 and 8, it was concluded in Ref. 8 that: "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%." Figure 7 shows the results of this wavelength changing and 10% POEM in the presence of 0.1% noise with no wavelength errors.

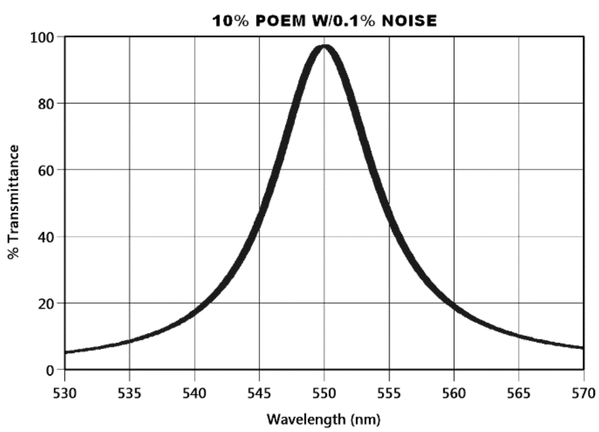

Figure 7

Figure 8 is the same as Fig. 7 with random wavelength errors of 0.5 nm giving some indication of how reproducible the wavelength must be for good results.

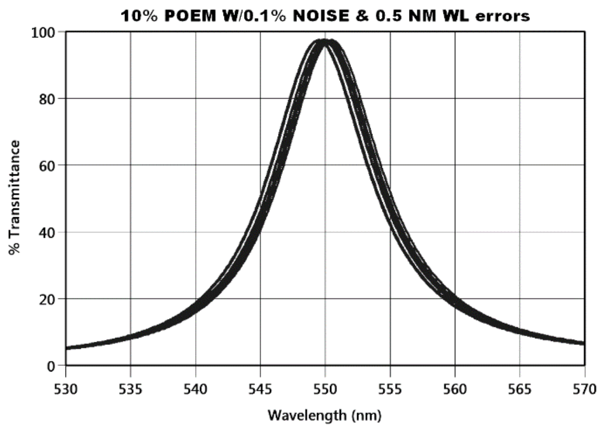

Figure 8 is the same as Fig. 7 with random wavelength errors of 0.5 nm.

Figure 9 is at a noise of 0.7% for comparison with the results in Ref. 8, and it shows that the techniques of this paper are on a par with those of Ref. 8. Therefore, changing wavelengths from layer-to-layer can be beneficial, if the wavelength is sufficiently reproducible.

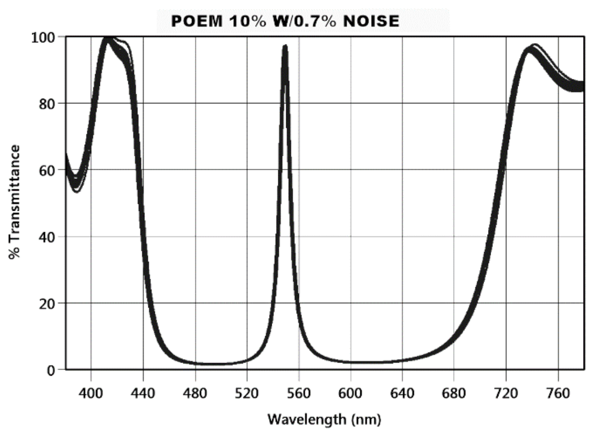

Figure 9 is the same as Fig. 7 with a noise of 0.7% for comparison with the results in Ref. 8.

CONCLUSION

The current work has shown by simulation that the monitoring wavelength can be changed as often as every layer in a design without loss of the error compensation effects. Direct monitoring on a single deliverable part, or at least a single monitor glass/chip, is still required for the maximum error compensation. However, as long as the monitoring wavelength can be changed reproducibly, the described scheme of changing wavelengths to terminate at points which are more sensitive than "turning points" could provide improved control and repeatability of the spectral results.

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