Sensitivity of Monitoring Strategies for Periodic Multilayers

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ABSTRACT

Semidirect level monitoring is reviewed graphically. The reproducability of periodic multilayers depends strongly on the monitoring strategy and the wavelengths chosen. Thickness sensitivity of monitoring strategies, and the optimum level and wavelength for optical trigger point monitoring are discussed.

INTRODUCTION

Macleod and Pelletier(1) described level monitoring and its application to optical coatings. Zhao(2) added further examples and analysis to level monitoring of periodic multilayers. We previously(3) analyzed the sensitivity of level monitoring and gave design strategies for general aperiodic multilayers. We here address the applications of the technique to periodic multilayers. We show that the sensitivity and therefore the reproducibility of the coating depends strongly on the monitoring strategy and the wavelengths chosen.

OPTICAL MONITORING SENSITIVITY

We will first reiterate from our earlier results(3) for the convenience of the reader. The use of reflectance amplitude or circle diagrams was described extensively by Apfel(4). We will review these briefly. The reflectance amplitude at the interface of two dielectric materials of indices n1 and n2 is defined as r, where $r=(n1-n2)/(n1+n2)$ The intensity of the reflected radiation is $R=rr^*$, where r^* is the complex conjugate of r. The reflectance of a thin film on a substrate where r1 and r2 are the reflectance amplitudes from the top and bottom of the thin film is given by $r=(r1+r2\exp(-i\theta))/(1+r1r2\exp(-i\theta)$. This is illustrated in Figure 1. The phase θ changes from 0 to 180 degrees as the thickness of the film goes from zero to one quarter wave (QWOT). Figure 2 shows this on a "circle diagram" or reflectance amplitude plot for a QWOT of magnesium fluoride on crown glass. We are all familiar with the resulting spectral curve of the single layer antireflection coating (AR)

We deal here exclusively with what is called semidirect optical monitoring. This means that every layer is deposited on a single monitor chip as it is being deposited on the part to be coated. Direct monitoring would be on the part itself. Indirect would be on more than one monitor chip and generally cannot compensate in a later layer for any errors of a previous layer. The potential benefits of error compensation are discussed in detail in References 1 and 2. This is a key point in the strategies described here. Figure 3 shows the optical monitor signal which will be produced by the SLAR coating of Figure 2. This is a small signal change and it therfore does not have much sensitivity of change in reflectance with change in layer thickness. Monitoring errors might be large.

As a further illustration of circle diagrams, we see the classical three layer broad band AR (BBAR) in Figure 4, its spectral curve in Figure 5, and its monitor curve in Figure 6.

Figure 7 shows the reflectance intensity contours (R=rr*) as a function of position on a reflectance diagram. We showed previously(3) that the rate of change of reflectance with optical film thickness varies with position on the reflectance amplitude circle diagram as is shown in Figure 8. This contour is essentially the same for all index materials, but the magnitude varies approxiamately as n-1. The sensitivity is greatest where the layer termination points are near an amplitude of 0.6 (36% reflectance intensity) on the imaginary (vertical) axis. This is for phase angles of about 90 or 270 degrees. The net effect is that it is most advantageous to have optical monitoring layer terminations occur as close to the maximum sensitivity point as practical in order to achieve the least error in the layer termination. It can be seen that the lowest sensitivity areas are on the horizontal (real) axis and at the outside of the circle. The usual turning point layer termination monitoring is at this axis and therefore far from optimal. The outside of the circle is where the reflection goes to 100% and there is no change in reflection with thickness. Practitioners have been avoiding this condition from the beginning, but come close to it in direct monitoring of Fabry-Perot filters.

PERIODIC MULTILAYERS

Figure 9 shows the theoretical performance of a long-wave pass filter from Macleod and Pelletier(1). The design is (H/2 L H/2)6 where H=2.35, L=1.35, and the substrate is 1.52. The level monitoring of this design without a precoated monitor chip is illustrated on the reflectance circle diagram of Figure 10. The optical monitor signal would appear as in Figure 11. As discussed by Macleod and Pelletier, this results in monitoring at a wavelength which has a "g" value of 0.542. Here the "g" value is the ratio of the wavelength at the quarter wave optical thickness of the layers to the wavelength under examination. They point out that the position of the monitoring wavelength can be chosen by using a precoating on the monitor chip. They also give an example which monitors at the wavelength of the edge of the passband at g=.8086. It is necessary to use a two layer precoating on the monitor chip in this second case in order to monitor at that wavelength. Figures 12 and 13 show the resulting circle diagram and the expected optical monitor curve at this wavelength.

In the case of Figures 10 and 11, Macleod and Pelletier(1) found "that the edge position varies by up to 5 per cent .... although excellent performance around the monitoring value is achieved." They found in the second case of Figures 12 and 13 that "the worst error in edge position is just under 0.4 per cent." We can visualize this from examination of Figures 7, 10, and 12. The sensitivity at the termination points of the first case are at about 0.35 of the maximum sensitivity and in the second case 0.78. The increased sensitivity and monitoring at the wavelength of greatest interest (the edge) in the second case have given the order of magnitude improvement over the first case as reported by Macleod and Pelletier.

We plot the locus of layer termination points for various values of "g" on a circle diagram in Figure 14. These points are for equal optical thickness layers of index 1.45 and 2.35. We see that the range of usable g-values is 0.0 to about 0.825 in this case. It can be shown that there is a periodic and symmetric repetition of these points for g-values greater than 1.0. Figure 15 is a plot of the sensitivity at the termination points in level monitoring. This was derived from the combination of Figures 7 and 14. We can see from Figure 15 that cases one and two fall at about .35 and .78 of the maximum sensitivity as we observed before. Note also that the edge of the band is the most sensitive place to monitor and that the half wave or g=2.0 is the least sensitive. The blocked band is excluded as a potential place to monitor because the reflectance rapidly approaches 100% where there is no change of reflectance with thickness.

Zhao(2) gives examples in his analysis with various g-values. Figure 15 is consistent with his findings and helps in the visualization of why the reproducibilty is markedly different from one monitoring wavelength to another.

CONCLUSIONS

We have made it easier to visualize

and understand the performance of several monitoring approaches and cases reported by others(1,2) with the aid of graphical representations. We have also shown that equal optical thickness quarter wave stacks should have the greatest monitoring sensitivity at the wavelengths of either edge of the blocking band. We have further shown a method to easily estimate the relative monitoring sensitivity of periodic multilayers at any wavelength of interest.

REFERENCES

(1 H. A. Macleod and E. Pelletier, "Error Compensation Mechanisms in Some Thin-Film Monitoring Systems," Opt. Acta <u>24</u>, 907 (1977).

(2) F. Zhao, "Monitoring of Periodic Multilayer by the Level Method," Appl. Opt. <u>24</u>, 3339(1985)

(3) R. R. Willey, "Optical Monitoring Sensitivity Improvement Using Graphical Methods," Appl. Opt. <u>26</u>, 729(1987).

(4) J. H. Apfel,"Graphics in Optical Coating Design," Appl. Opt. <u>11</u>, 1303(1972).

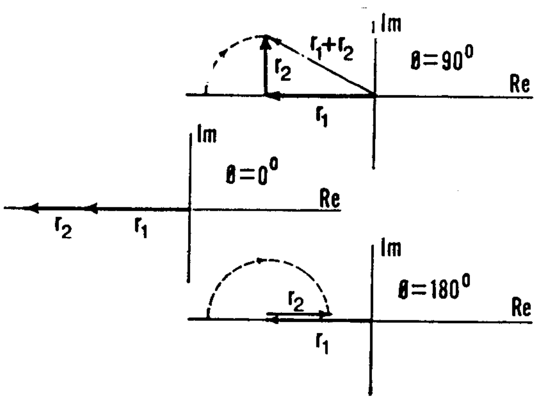

Fig. 1. Addition of amplitude vectors of reflections from the two surfaces of a thin film for various phase angles (thicknesses).

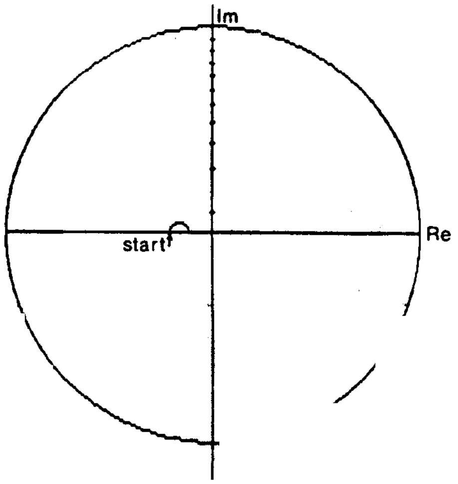

Fig. 2. Reflectance amplitude diagram for a quarter wave optical thickness (QWOT) of magnesium fluoride on a crown glass substrate.

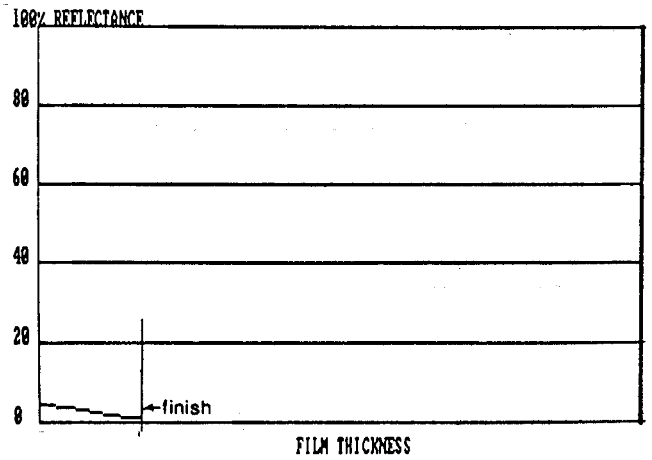

Fig. 3. Optical monitor signal change as the film thickness increases during deposition of a QWOT of magnesium fluoride on a glass substrate.

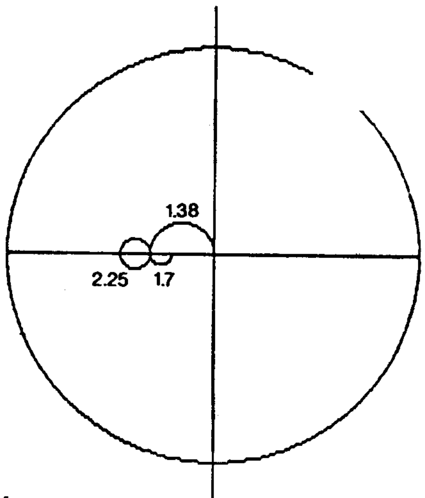

Fig. 4. Circle diagram for a classical quarter-half-quarter wave broad-band antireflection coating at the design wavelength.

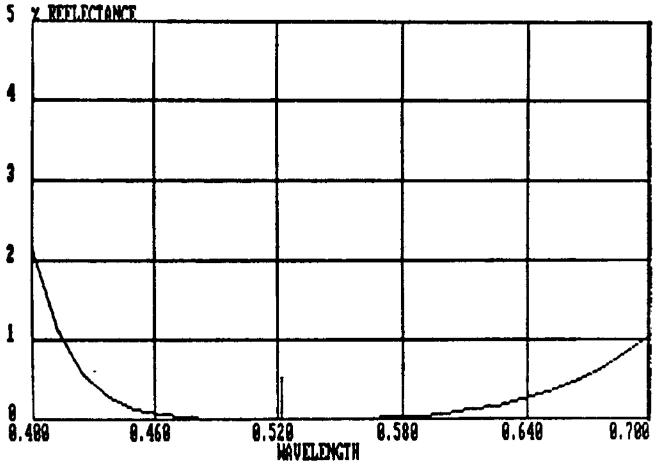

Fig. 5. Spectral reflectance curve for a quarter-half-quarter antireflection coating showing the design wavelength at .520 micrometers.

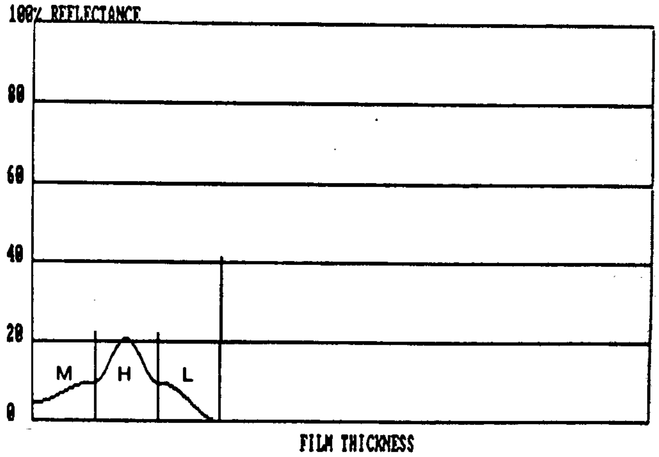

Fig. 6. Optical monitor signal on a single monitor chip (semi-direct monitoring) for the classic quarter-half-quarter antireflection coating.

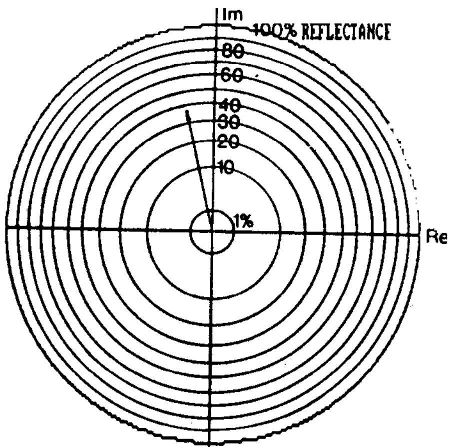

Fig. 7. Reflectance diagram of equal percent reflectance intensity contours. The vector represents a reflectance intensity of about 36% and a reflectance amplitude of 0.60.

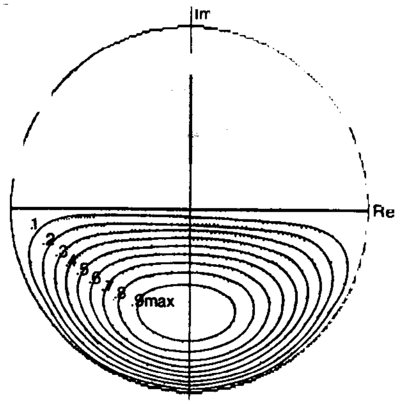

Fig. 8. Rate of change of reflectance intensity with optical film thickness as a function of position on the reflectance circle diagram for material of index 1.38. Values are symmetric about the real axis.

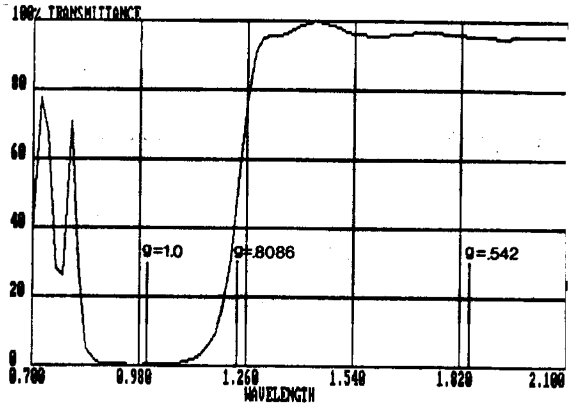

Fig. 9. Theoretical transmittance of LWP filter from ref. 1. Design is (H/2 L H/2)6. Values of g are indicated for two monitoring wavelengths discussed.

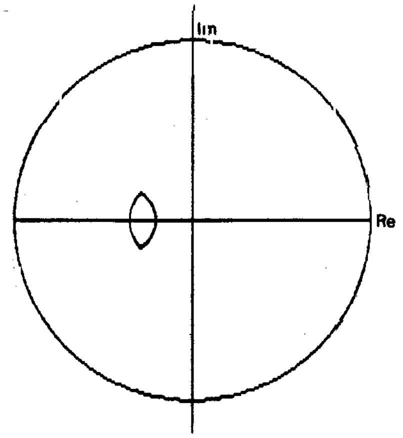

Fig 10. Circle diagram for Macleod and Pelletier(1) example with no precoating on monitor chip; g=.542.

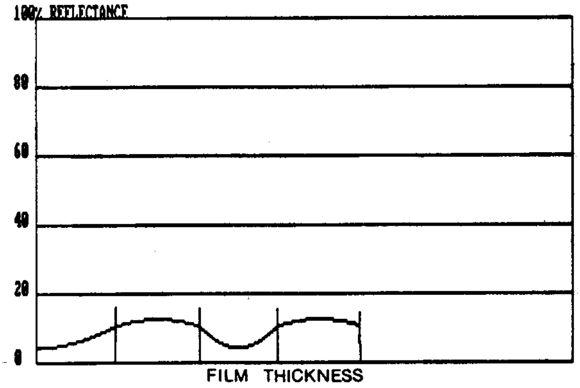

Fig.11. Optical monitor signal on a single monitor chip (semi-direct monitoring) for the unprecoated case of Figures 9 and 10

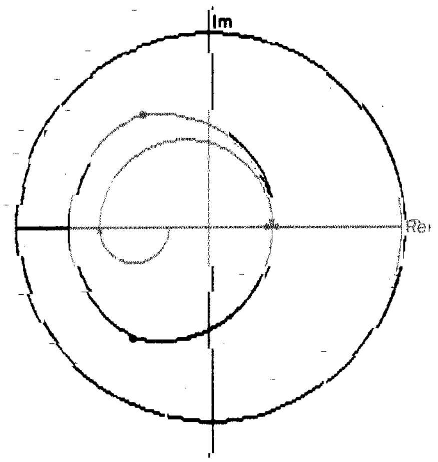

Fig.12. Circle diagram for a two layer precoated case where the stack is monitored at g=.8086.

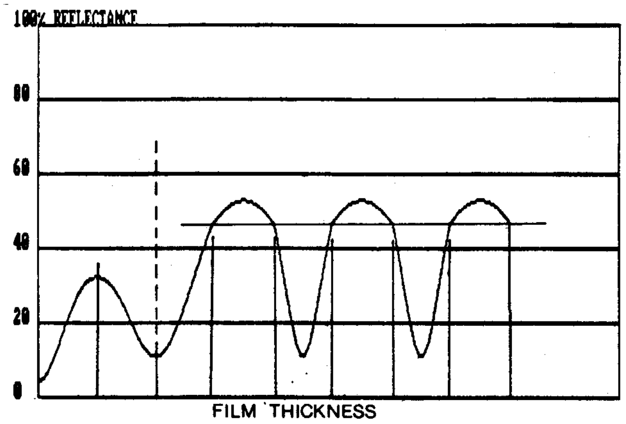

Fig.13. Optical monitor curve of the two layer precoated case of Figures 9 and 12 where g=.8086.

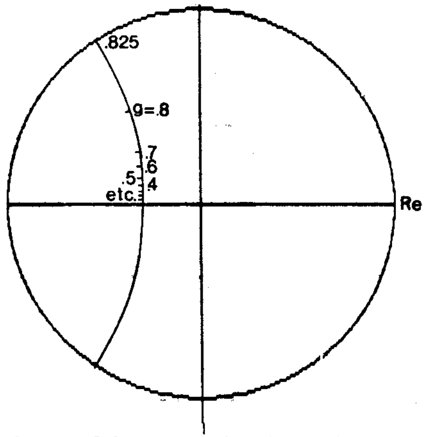

Fig.14. Locus of layer termination points versus the monitoring g-value in single level monitoring of equal optical thickness layers of index 1.35 and 2.35.

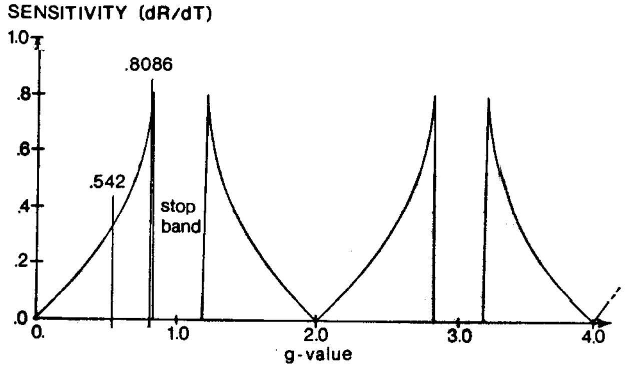

Fig.15. Plot of level monitoring sensitivity as a function of g-value for equal optical thickness layers of index 1.35 and 2.35