REALIZATION OF A VERY BROAD BAND AR COATING

Ronald R. Willey
Opto Mechanik, Inc., P.O.Box 361907
Melbourne, FL 32935, United States

ABSTRACT

In previous papers we have described the underlying principles of very broad band antireflection coating design based on inhomogeneous layers. We further described the modification of such designs by approximating the inhomogeneous layers with a series of thin homogeneous layers. The number of these homogeneous layers was then reduced to a minimum which could satisfy certain spectral requirements. In this paper we describe our experience in working to actually produce such a coating in a practical environment. We again demonstrate that many things are easier to design on paper than to build. This particular coating illustrates some of the limitations of ordinary coating processes and the ability to control deposition over a large area.

INTRODUCTION

Some years ago, the author was faced with a production process for an AR in the visible and 1064 nanometers which had a low yield in production. This generated two questions which have motivated several investigations and papers since that time. First is the question of what are the basics of designing a broad band AR coating? Second is how can one control the production to get a reasonable yield? We have reported on the principles, possibilities, and limitations of broad band AR coating designs in recent publications(1,2,3,&4). We adapted the design reported in reference 1 to be optimum from 400 to 700nm and at 1064nm using SiO2 and TiO2. For reasons described below, we later changed the design to MgF2 and TiO2 and were able to eliminate one layer with no loss in performance. The resulting performance of the eleven layer design is shown in Figure 1. The challenge of actually producing a coating which approaches the design performance is the subject of this paper.

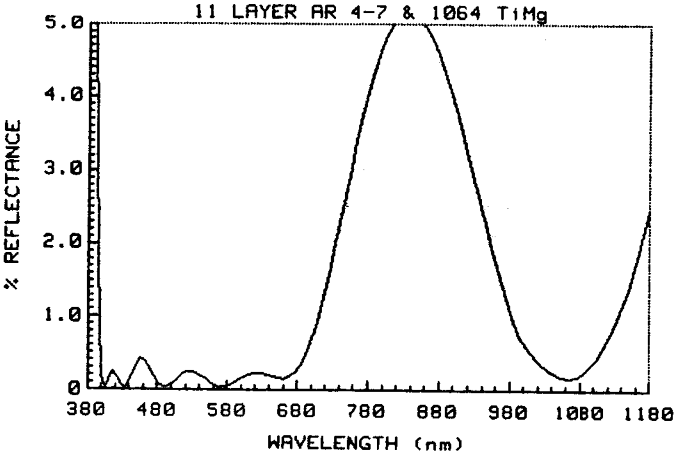

Fig. 1. Eleven layer Ar design for 400-700nm and 1064nm. H=TiO2 and L= MgF2(1.38). Design: .1052L .04H .04H .5697L .08H .0653L .5915H .0465L .1025H .2483L.

EXPECTED EFFECTS OF ERRORS

We simulated the effects of random errors in each of the 11 layers. Random errors with a standard deviation of 2.6% of a quarter wave at 584nm (and limited to 5.2% maximum error) would yield results as shown in Figure 2.

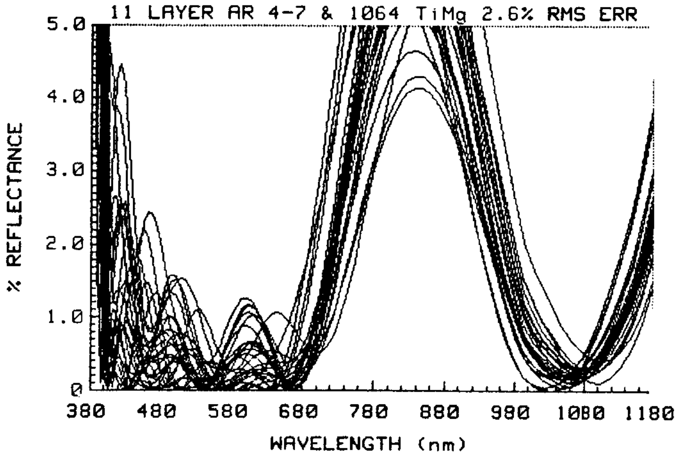

Fig. 2. Effect of random layer errors with standard deviation of 2.6% RMS of a QWOT at 584nm on the design of Figure 1.

Our experience leads us to believe that layer thickness errors are typically of this order of magnitude in practice. This leads to some major concern as to whether such a coating is achievable unless some form of error compensation can be used. Figure 3 shows the effect of 0.65% RMS errors, and this result is more in accordance with what is required for this coating application. Zhao(5) showed that error compensation can be achieved at and near the monitoring wavelength if all layers of a stack are monitored on one chip and at the same wavelength. In looking at Figure 2, we see that the effect of the errors is most severe at the shortest wavelengths and not too severe at the 1064nm band. This led us to choose the monitoring wavelength near 400nm and on a single monitor chip.

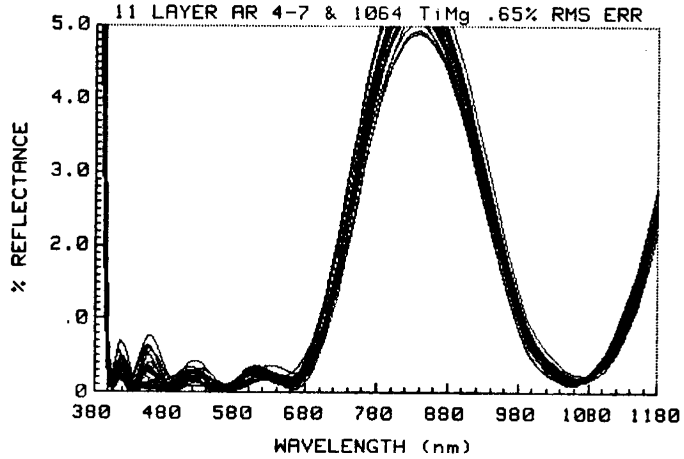

Fig. 3 Effect of random errors of 0.65% RMS as in Figure 2.

MONITORING PLAN

Figures 4 and 5 show the monitoring plan which evolved. We previously investigated the relative sensitivity of monitoring strategies(6). We showed the desirability of making cuts away from turning points and as near as practical to 36% reflectance for maximum sensitivity in terms of rate of change of reflectance with thickness of the layer. The previous work examined extensively the use of precoated monitor chips to enhance sensitivity. We have not yet applied this additional step to the present case, but it might further improve the yield of the process. The design has several layers that tend to be too thin for easy optical monitoring. This is common to many coatings of this type. Crystal monitoring is usually most appropriate in these cases, but there can be significant variability and errors if the crystal readings are not sufficiently calibrated. We usually favor optical monitoring because it controls the parameter most important to the result, the optical reflectance. Schroedter(7) described a technique which combines the best of the optical and crystal capabilities to give what we consider the optimal approach to monitoring. He correlated the optical signal (quasi-sinusoidal) with the crystal readings by computer curve fitting in real time. This correlation becomes better with increasing optical thickness. After the first quarter wave optical thickness (QWOT) turning point has been passed, the crystal is well calibrated and can be used to give a very good cut point anywhere between 1 and 2 QWOT's. After the second QWOT, the crystal is even better calibrated, etc.

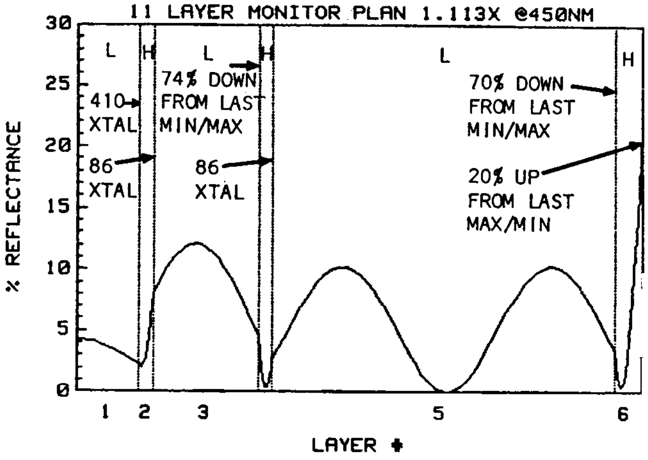

Fig. 4 Monitoring plan for first 6 layers of coating including optical and crystal terminations of layers (cuts). Monitored at 432nm.

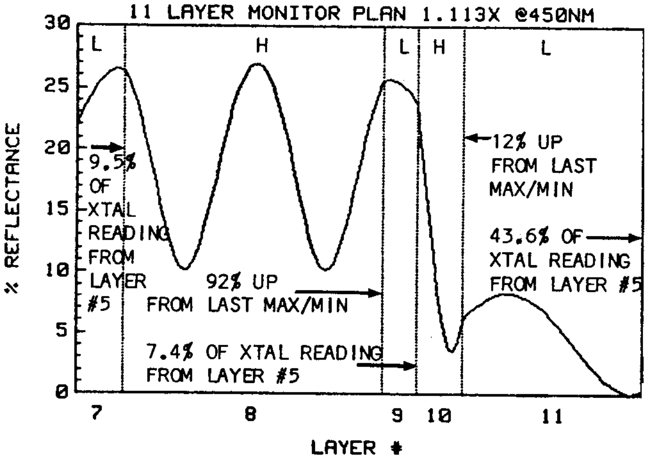

Fig. 5 Continuation of monitoring plan for layers 7 to 11.

We have applied the basic concept of Schroedter in a manual mode to this case. The first and second layers as seen in Figure 4 are thin and not well suited to optical monitoring. The best calibration available in this case for the optical thickness of the high(H) and low(L) materials versus the crystal readings is data from the most recent previous run under the same conditions. The crystal readings are calculated on the basis of the values of the readings from the previous run on layer 5 for L and 8 for H. Layer 3 is cut optically as 74 percent from the previous peak, in terms of the reflectance swing from the minimum of layer 2 to the maximum of layer 3. If the indices of the H and L are somewhat different from the design values, the absolute reflectance of the extrema will not be correct, but the relative reflectance will be nearly correct. We have found this technique to be a reliable way to make optical cuts, and insensitive to index or photometric inaccuracies. Layer 4 is again a crystal cut based on the previous run calibration. Layer 5 is an optical cut 70% down from the last max/min. The crystal reading from layer 5 is a calibration of the L material to be used on later layers 7, 9, and 11 in the current run. Layer 6 could be cut either optically or by crystal, but we finally chose optical as most sensitive and reliable in this case. Layer 8 is an optical cut and calibrates the crystal for H in future runs. From experiment, we found layer 10 to be best cut optically, although its thickness could be well controlled by the calibration from layer 8. We will come back to this issue below in the discussion of error compensation. Layer 11 could be cut either way, but we found crystal somewhat preferable because the cut is too close to the turning point for good photometric sensitivity. An alternative for the system might be to monitor at a slightly shorter wavelength so that layer 11 would go enough beyond the turning point to get a good optical cut. This would have to be viewed with respect to its effects on the cuts of the other layers. This is the plan which was executed by the operators in producing the results described below.

EXECUTION OF THE PLAN

The first attempts to produce this coating were with SiO2 and TiO2 from an electron beam gun. We encountered a major problem. The monitor chip could be made to have a very good result, but the witness chips in the planet would vary significantly from the monitor and (more importantly) from run to run. We attribute this to the difficulty of achieving a reproducible and constant angular material distribution from SiO2 evaporated from a gun. We changed the design and process to TiO2 from a gun and MgF2 from a boat and found the results more reproducible from run to run. This also had the small advantage of using the lowest available index for the last layer. We previously discussed(1) the benefits of a low index last layer in getting the lowest reflectance over a broad band.

The results of the first test run of the new design are shown in Figure 6. The actual spectral measurements from the witnesses and the monitor chip were inserted as design goals in the FILMSTAR program by FTG Software. The thicknesses were optimized to fit the

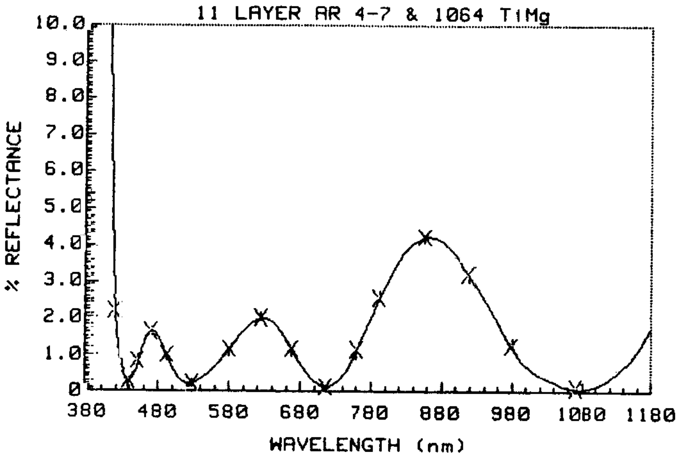

Fig. 6 Results of first test run with design of Figure 1 and monitoring plan.

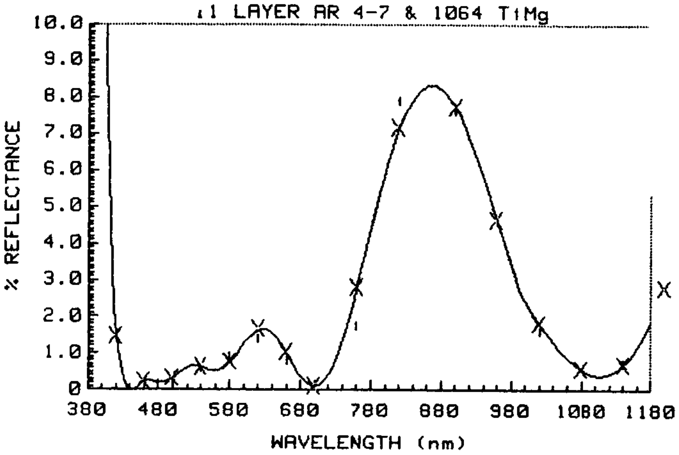

Fig. 7. Results of second test run after preliminary adjustments based on the results of Figure 6.

resulting reflectance spectrum to the measured values. The resulting thicknesses were compared to the design and used to adjust the crystal and optical monitor plan for the next run. We found, not surprisingly, a different tooling factor between the monitor and the witnesses in the planets for each material. As a result, the coating on the monitor chip needs to be something other than the "perfect AR" in order for the witnesses in the planets to have the coating desired. The results of the second test run based on these adjustments are shown in Figure 7. The adjustment process was repeated. The results of the next run is the best curve seen in Figure 8.

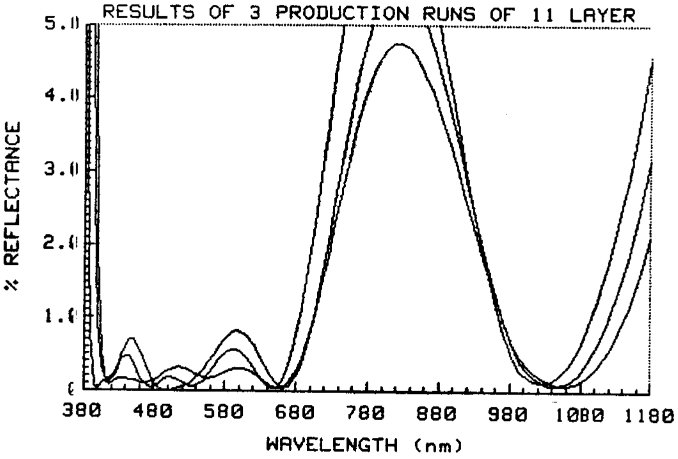

Fig. 8. Results of three "production" runs after second adjustment based on results of Figure 7.

PRODUCTION RESULTS

Two additional subsequent production runs with the same parameters as the third test run are plotted in Figure 8. When we compare Figure 8 with Figure 3, we find similar results. This implies results that are nearly the same as those predicted for random layer errors of about 0.65% of a QWOT RMS. This is a pleasant surprise as compared to what might be expected based on Figure 2. The measured data on the three results in Figure 8 were fit as above to determine the thickness errors from the design. The RMS errors were 2.63, 2.95, and 4.40% respectively, and the worst errors in each run were 5.20, 7.60, and 10.84%. The effective monitoring wavelength was about 400nm. It can be seen from Figure 8 that a satisfactory result was achieved. The 1064nm band was well controlled and reproducible with less than 0.25% reflectance in each case. The 400 to 700nm range averaged less than 0.3% with a worst peak of 0.7%. There was however one small problem which will need to be fixed. The transmittance of a witness coated on two sides was not as good as expected due to scattering and possible absorptance. We believe that this can be corrected by adjusting the process parameters of the TiO_2.

CONCLUSIONS

We conclude that the scheme selected incorporates the benefits of error compensation because the results are so much better than predicted on the basis of random (uncorrelated) errors. The use of optical cuts tends to correct for some errors in previous layers similar to what happens in typical narrow bandpass filter monitoring as described by Macleod and Pelletier(8). If the previous layer was too long or too short, the current layer provides just enough material to bring the reflectance as near as possible to the desired reflectance. Monitoring at the short wave end where the effect of random errors would be most severe, has seemed to be the correct choice and in agreement with the findings of Zhao(5) that the area nearest the monitoring wavelength is best controlled. We have seen that indirect optical monitoring can have sufficent control for the materials selected (TiO_2 and MgF_2), but that our process for SiO_2 is inadequate for this requirement. We have shown that the design principles described previously can be reduced to practical coatings, and we have described the steps which we took to reduce this particular coating to practice.

REFERENCES

1. R.R. Willey, "Another viewpoint on antireflection coating design," SPIE 1191-19, London, 1989.
2. R.R. Willey, "Rugate broadband antireflection coating design," SPIE 1168-26, San Diego, 1989.
3. R.R. Willey, "Graphic description of equivalent index approximations and limitations," Appl. Opt. 28, 4432, 1989.
4. R.R. Willey, P.G. Verly, and J.A. Dobrowolski, "Design of wideband antireflection coating with the Fourier transform method," SPIE 1270-05, The Hague, 1990.
5. F. Zhao, "Monitoring of periodic multilayer by the level method," Appl. Opt. 24, 3339 (1985).
6. R.R. Willey, "Optical thickness monitoring sensitivity improvement using graphical methods," Appl. Opt. 26, 729 (1987).
7. C. Schroedter, "Evaporation monitoring system featuring software trigger points and on-line evaluation of refractive indices," SPIE 652, 15 (1986).
8. H.A. Macleod and E. Pelletier, "Error compensation mechanisms in some thin film monitoring systems," Opta Acta 24, 907 (1977).