Design of Optical Coatings Taking Consideration of Probable Production Errors

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Key Words: Optical coating design; Layer thickness errors; Optical coating production; Layer thickness tolerances

ABSTRACT

Practical optical coating designs need to be produced by processes that have some finite variability or errors in layer thickness and index of refraction. The optimum design for production in some cases may be the same as the optimum without consideration of these production errors. However, there are possibly a few classes of designs where optimizing the design to minimize the effects of these errors might improve the probable production yield. We report on the investigation of which classes might be improved by design techniques considering the effects of probable production errors versus which classes cannot be significantly improved. We further report on the influence of different error distribution assumptions such as: random errors uniformly distributed within a tolerance range, worst case error distributions, and various sensitivities to errors which might realistically represent those in actual practice. Proper consideration of these influences on the design can require orders of magnitude more computation time, but this is not as great a burden in this era of faster computation as it would have been in the past.

INTRODUCTION

Virtually all optical thin film design procedures used today optimize a design without consideration of the effects of production errors. Here we have studied whether the use of design procedures which do include probable production errors would lead to improved results in the real production environment. The focus of this study has been on the effect of random errors where no "self-compensation"[1] effects apply. The use of crystal monitoring or optical monitoring which uses one monitor chip per layer would be examples of this sort of uncompensated errors. We have examined optimizations including the following forms of error inclusion: 1) random errors of some magnitude and bound, 2) worst case errors of a given magnitude, 3) total sensitivity of the merit of the design, and 4) sensitivity of the change in the merit of the design.

PROCEDURES

The thin film design software which we ordinarily use [2] has the capability to optimize a design with respect to the results of any merit function that can be calculated in a "Basic" subroutine using the evaluated spectrum and parameters of the design. We employed this workbook capability with Basic subroutines written to implement the procedures 2, 3, and 4 mentioned above.

At the start of this study, the thought was to use as the merit function to be optimized a summation of the merit of a fixed number of spectra resulting from random layer thickness perturbations of the nominal design. Figure 1 shows such effects for 100 spectra of random errors in a range of -3 to 3 nm on each layer of a four layer AR design. However, it was discovered that, for even large numbers of spectra, the noise in the resulting merit was too large to allow convergence of any of the optimization techniques attempted. Figure 2 shows that there is about 5% (std. dev.) noise in the merit even if over 1000 spectra were used per optimization iteration. The randomness of the process defeats optimization, so we abandoned this approach.

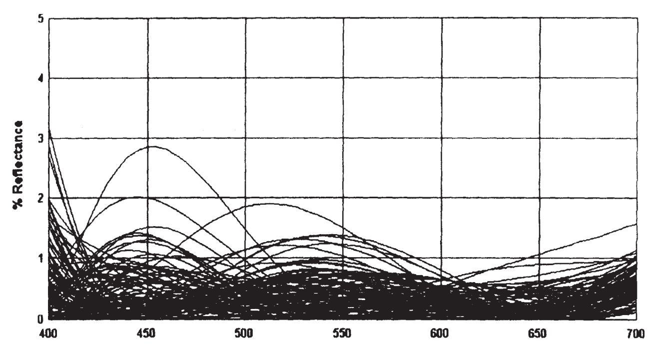

Figure 1. Reflectance spectra of a nominal four layer AR design with 100 cases of thicknesses perturbed by random thickness errors in the range of -3 to 3 nm.

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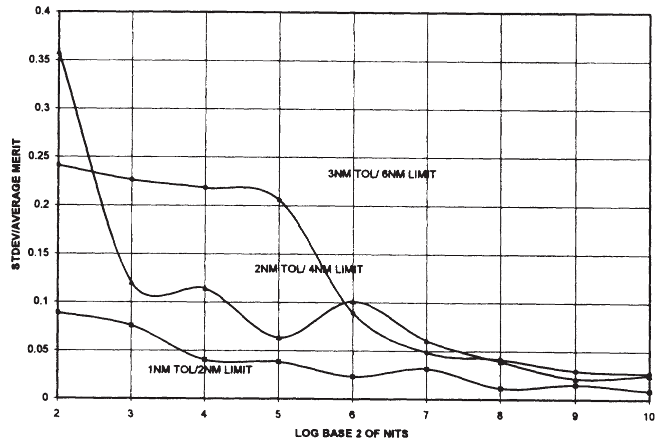

Figure 2. The standard deviation divided by the average (de)merit versus the number of iterations included in the evaluation of the effects of random thickness errors in the ranges of 1, 2, and 3 nm. The random errors of normal distribution were truncated at twice the standard deviation.

The second approach taken was to evaluate every error at its worst case plus and minus limits and compute a merit based on all of the possible combinations. We refer to this as the "Worst Case" optimization procedure. This removes any random noise effects and is a reasonable indication of the effects of thickness errors on the design. The number of combinations is 2 to the N^{th} power, where N is the number of layers. For two layers, this is four cases to be evaluated; but for 13 layers, this would be 8192 cases, etc. This turns out to be a reasonably acceptable amount of computing time for perhaps 8 layer designs, but 13 layer designs are best run overnight on a 400MHz PC. Most of our study was done with error ranges that were either 1 or 3 nm.

The third approach used was to minimize the sensitivity of the total merit of the design to errors of a given magnitude (typically 1 or 3 nm). Here, the merit is the sum of the merits of the design with each layer perturbed in turn by the given error in thickness. We call this the "Total Merit Sensitivity."

The fourth approach was similar to the third except the merit was the sum of the magnitude of the change in the merit from the nominal design merit or the "Delta Merit Sensitivity."

We used these techniques to study the optimization of several types of optical coating designs to see if any of the types could be significantly improved when under the influence of realistic production errors. The types studied include: two, three, four, and eight layer AR's; a 50/50 beamsplitter; a constant slope filter across the visible (such as for color correction); a long and short wave pass edge filter; and a polarization filter. Narrow bandpass Fabry-Perot filters were not considered here because it is generally known that they need the error compensation effects to be produced in practice.

RESULTS

There are classically two solutions to the two layer "V-coat" design for a single wavelength AR. Figure 3 shows V1 and V2 results for an AR at 550 nm where the first layers are index 2.25 and the second 1.46 on 1.52 substrates. The thicknesses in nm for V1 are18.06 and 123.47; for V2 they are 229.94 and 68.83. We refer to these as the short and long starting layer designs, V1 and V2. V2 is more than twice the physical thickness of V1; therefore, the percentage of layer thickness of a 1 or 3 nm error would be correspondingly smaller for V2 than V1. However, the reflectance at 550 nm of V1 is the least effected by a given error because it is spectrally broader. Figure 4 shows the sensitivity of the merit (demerit) of each of these layers to thickness errors. Note that the effects of the errors on the merit are essentially symmetric about the nominal design. None of the optimization procedures was found to be able to improve the performance of these designs in the presence of thickness errors.

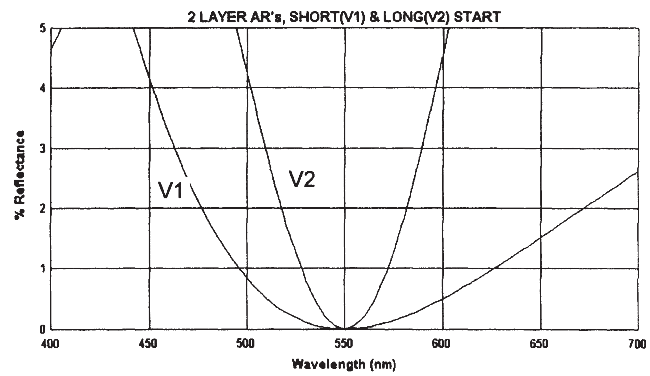

Figure 3. Two solutions to the two layer "V-coat" design for a single wavelength AR at 550 nm. The first layers are index 2.25 and the second 1.46 on 1.52 substrates. The thicknesses in nm for V1 are18.06 and 123.47; for V2 they are 229.94 and 68.83.

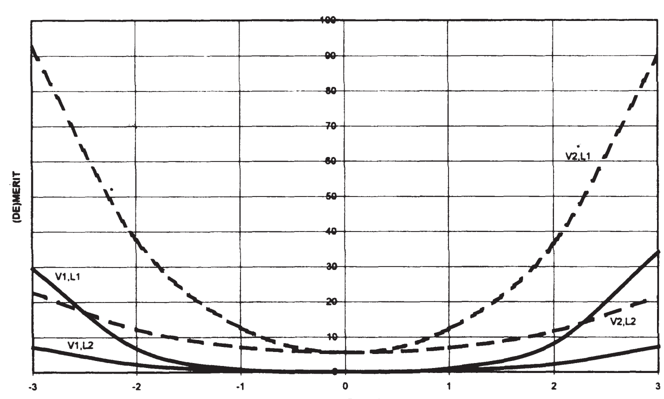

Figure 4. Sensitivity of the (de)merit to thickness errors in each of the layers of the two V-coat designs.

Classical three layer AR's of medium, high, and low index layers gave similar results.

All of the optimization procedures were applied to the four layer AR design shown in Figure 5 and labeled "4L." The results of 3 nm errors on the normal design are seen in Figure 1. After optimization with 3 nm errors using the Worst Case procedure, the resulting design was as seen in the "ERROPT4" spectrum of Figure 5. Figure 6 shows the application of 100 scans of random error on this latter design. The other optimization procedures showed no significant difference from the nominal design. A comparison of Figures 1 and 6 shows that the mean reflectance is lower in the 550 nm region and higher at the 450 nm region for the ERROPT4 design than the normal 4L design. The weighting of the spectrum for this merit function was flat across the 450 to 650 nm region and linearly increased to twice the tolerance at the 400 and 700 nm ends. We know from previous experience [3] that the short wavelength end of the spectrum tends to be more affected by errors than the long wavelength end. It appears that the optimization including the effects of errors has offset the nominal design in such a way as to improve the result in the central and more weighted region at the expense of the less weighted outer regions. Figures 7 and 8 show the (de)merit sensitivity of each of the four layers of the nominal and error-optimized designs. It appears that the procedure has in effect reduced the impact of the most sensitive first layer by offsetting the symmetry and compensating with the other layers.

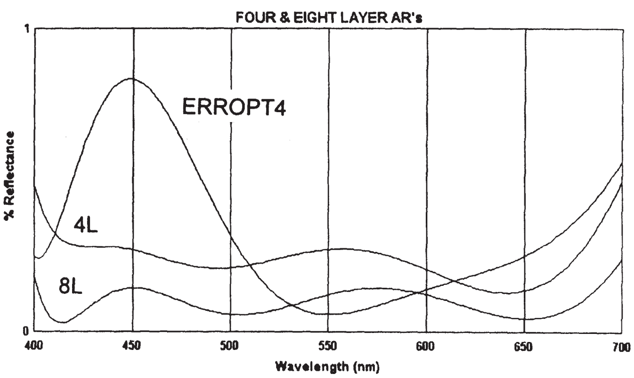

Figure 5. Reflectance spectra of a nominal four layer AR design (4L), the same design reoptimized considering 3 nm errors (ERROPT4), and a nominal eight layer design (8L).

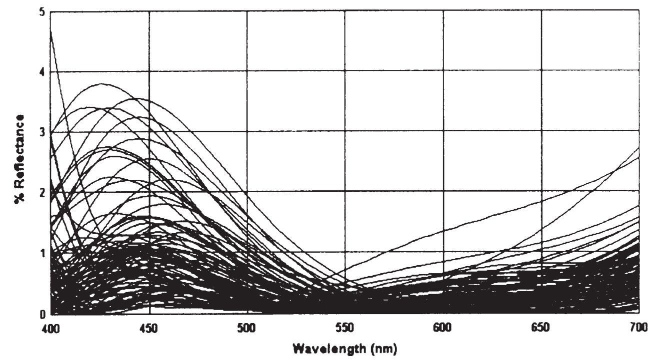

Figure 6. Reflectance spectra of ERROPT4 design with 100 cases of thicknesses perturbed by random thickness errors in the range of -3 to 3 nm.

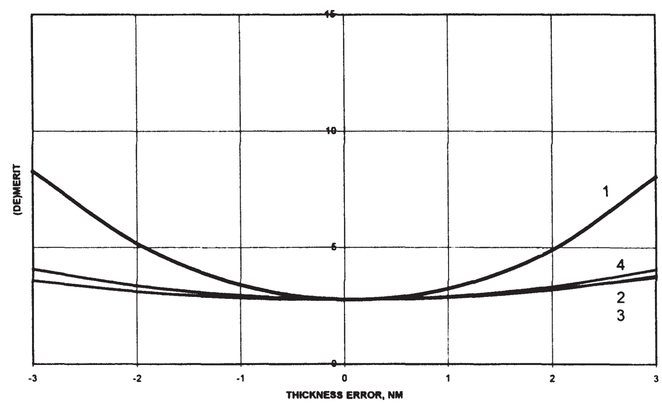

Figure 7. Sensitivity of the (de)merit to thickness errors in each of the layers of the nominal four layer AR design.

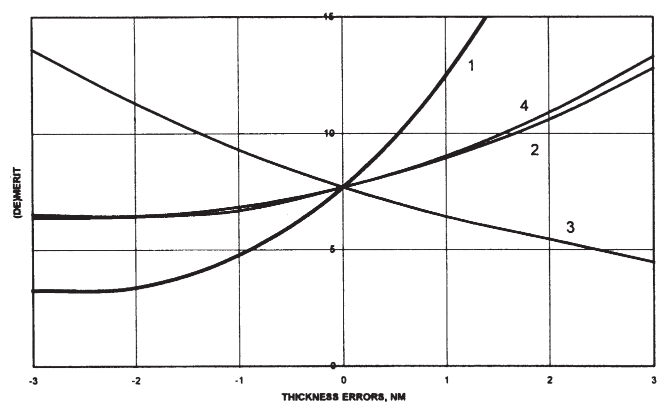

Figure 8. Sensitivity of the (de)merit to thickness errors in each of the layers of the ERROPT4 four layer AR design which was reoptimized from the nominal design including the effects of 3 nm error.

The various optimizations gave no noticeable improvement in the eight (8) layer AR with errors shown as "8L" on Figure 5. However, it is interesting to note in comparing Figure 9 for the nominal eight layer design with the nominal four layer in Figure 1, that there is no significant difference in the results when under the influence of 3 nm errors! We also found the same to be true for 1 nm errors. It therefore seems that the improved design performance of the eight layer AR over the four layer cannot be achieved in production unless the random errors are significantly less than 1 nm or some error compensation monitoring strategy is used in the production process.

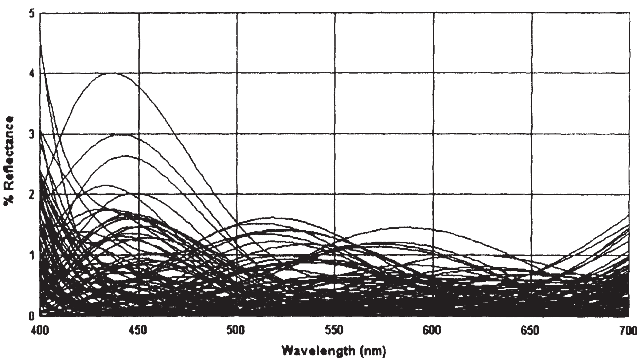

Figure 9. Reflectance spectra of the nominal eight (8) layer AR design (8L) with 100 cases of thicknesses perturbed by random thickness errors in the range of -3 to 3 nm.

All of the other design types studied (beamsplitter, constant slope, long and short wave pass, and polarization filter) were not seen to have any benefit from optimization including error effects.

CONCLUSIONS

We have not been able to discover any class of coatings which gain a significant benefit from the optimization with respect to the expected random errors of production. The only possible and slight exception is the four layer AR. It has not been surprising to find that normal designs result in each layer thickness lying at a minimum of the (de)merit function wherein a movement from the nominal in any direction will increase the (de)merit (see Figures 4 and 7). Since this is also the point of the zero first derivative of the (de)merit with respect to thickness, the sensitivity to small errors is a minimum. We have seen evidence (not shown here due to lack of space) that the effects of error optimization become somewhat more beneficial as the size of the errors increases; however, these larger errors would seem to be inconsistent with the normal requirements that we must meet in practice.

It is further interesting to see (but not new) that V1-coat is to be preferred over the V2. We have also illustrated that highly refined AR's of more than four layers for the visible spectrum may not be worth pursuing unless very tight process control can be achieved and/or more sophisticated monitoring and control strategies employed.

ACKNOWLEDGEMENT

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