Broadband Antireflection Coating Design Performance Estimation

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ABSTRACT

The application of a few basic principles, some empirical data, and experience is applied to estimate the average residual reflection expected in an AR coating as a function of bandwidth, wavelength, overall thickness, substrate index, available coating materials, and number of layers. This can be a useful tool for not only the thin film designer but also the non-designer or system engineer to predict the performance of an AR coating for a given application.

INTRODUCTION

We have addressed the problem of understanding[1], designing[2], and producing[3] very broadband antireflectance (VBBAR) coatings over the past several years. Here we pull together those results and further investigations to provide a tool for the engineer or designer to estimate the performance which can be expected from a VBBAR design before the design process is started. To this end, we have fit our cumulative results to an equation for the average reflectance in the AR band as a function of the four major variables. These variables are bandwidth (B), index of refraction of the last layer (L), overall optical thickness of the coating (T), and the difference (D) between the highest and lowest indices used (except for the last layer). We will show how this was developed, what its limitations are, how to apply it, and what factors are of major and minor importance.

PROCEDURE

A series of designs were optimized over fixed bandwidths to give the lowest average reflectance in the band while varying each of the major factors. These empirical results were used to determine the reflectance as a function of these variables. Figure 1 shows such a series to find the average reflectance (R) as a function of bandwidth (B) where the L,T, and D were held constant. In effect, we were taking the partial derivative of R with respect to B. Figure 2 shows the change in R with respect to overall optical thickness (T) while B,L, and D are fixed.

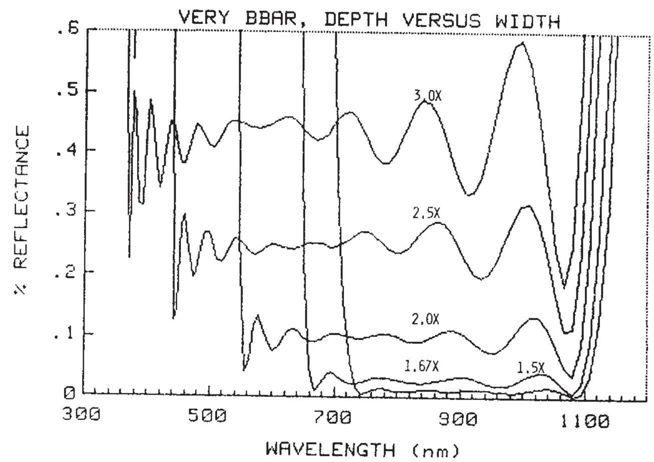

FIG. 1. Variation of minimum average Reflectance with bandwidth for T = 3,0 cycles.

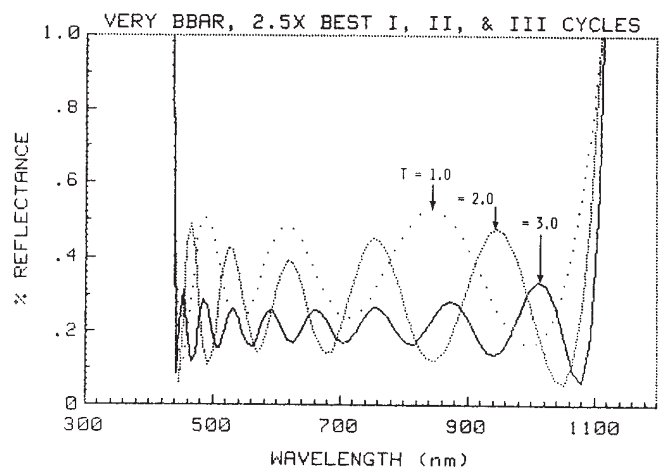

FIG. 2. Variation of minimum average Reflectance with overall optical thickness.

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The four factors B,L,T, and D were found to be the major variables affecting the minimum average reflectance which can be achieved. We also found that the minimum number of homogeneous layers required can be predicted. We will discuss this below. It was found that the substrate index has no major effect on the minimum reflectance possible in the ranges examined. We were also surprised to find that the number of indices used in the design should be as small as possible (two) for the best design results. This may be contraindicated, however, when environmental and physical factors are considered. For example, we have had the most success with titania and silica stacks with a last layer of magnesium fluoride. The most major influence on the minimum average reflectance is the index of the last layer which needs to be as low as practical. We have discussed the reason for this extensively in our previous work [1,2,3]. This is why we use magnesium fluoride as the last layer. It would also be desirable from the design point of view to also use it in the stack to have D as large as possible. However, we have found [3] such stacks to have excessive scattering and therefore we use silica instead.

Other minor observations include that the frequency of the residual ripple in the AR band is proportional to the overall optical thickness, T, and it is independant of the number of layers in the design.

THE FORMULAS

The collection of data of R versus B,L,T, and D was empirically fit to functions over the range of the investigation to arrive at Equation 1.

Here the product of the bandwidth (B) times the last (lowest) index (L) minus one is raised to the 3.4 power. One divided by the overall optical thickness (T) is taken to the .63 power. The difference in index between the layers of the stack (D) is subtracted from 1.2, squared and added to .42. The product of these three factors is the minimum average reflectance in percent (%) that can be expected in designs within the applicable limits. The ranges over which these variables have been thus far shown to give reasonable estimates is as follows:

B from 1.5 to 3.0
L from 1.17 to 1.46
T from 1.0 to 3.0
D from 0.4 to 1.2

To set these in perspective, let us point out that these studies have been for the visible and near infrared spectral range. B, for example was tested from a 400-600nm (1.5) bandwidth to a 400-1200nm (3.0) bandwidth. The lowest real index (L) which we use is about 1.38, but we have studied (in design) the use of imaginary materials down below 1.1 and real materials such as silica up to 1.46. The overall optical thickness of the stack (T) is given in waves of the longest wavelength of the band which we have previously [2] referred to as cycles. In coatings on high index substrates like germanium where there are several lower and intermediate indices between the substrate and an index of 1.0, we have shown [1] that 1/2 cycle or “step-down” coatings are most advantageous. In the case of visible band materials, there is not a significant choice of lower index materials to make the step-down approach practical. The simplest broadband solutions in the visible are of the classical three layer type which is in effect a one-cycle design. This is why the present work is confined to a T-range of 1.0-3.0. The D-values come from the differences between high index titania at up to 2.58 and down to low the index of magnesium fluoride at 1.38 and combinations of intermediate materials.

RESULTS

We will now compare the empirical results with the values that would be estimated by Eqn. 1. Figure 3 shows the variation of R with bandwidth while other factors are held constant. The x’s are the empirical results and the curve is the prediction of the formula. The fit shows a generally good but pessimistic prediction. A straight line projection function of (B-1.7) was also considered, but discarded because the chosen function fits additional T-values better.

$$R_{AVE}(B,L,T,D)\% = (B(L-1))^{3.4} \left(\frac{1}{T}\right)^{.63} ((1.2-D)^2 + .42) \qquad \text{EQN.}(1)$$

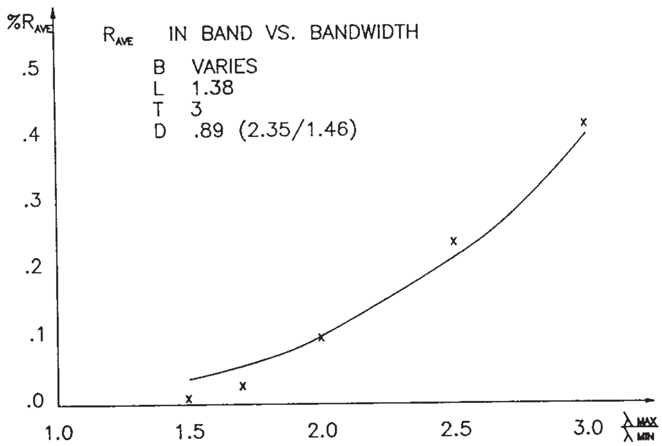

FIG. 3. AVERAGE REFLECTANCE IN BAND VERSUS BANDWIDTH. CURVE IS FROM FORMULA, X'S ARE EMPIRICAL DATA.

Figure 4 shows R versus L which points out the advantage of lower indices if they could be found or simulated. Figure 5 shows many test cases where the number of layers in the designs were progressively reduced until the results passed through a minimum R. It was counterintuitive to find that the performance improved slightly as the number of layers was reduced, while keeping T constant, down to some minimum. The minimum number of layers is approximately equal to 6T+2, which is an interesting and useful result. Further reduction in the number of layers then causes the achievable results to degrade rapidly.

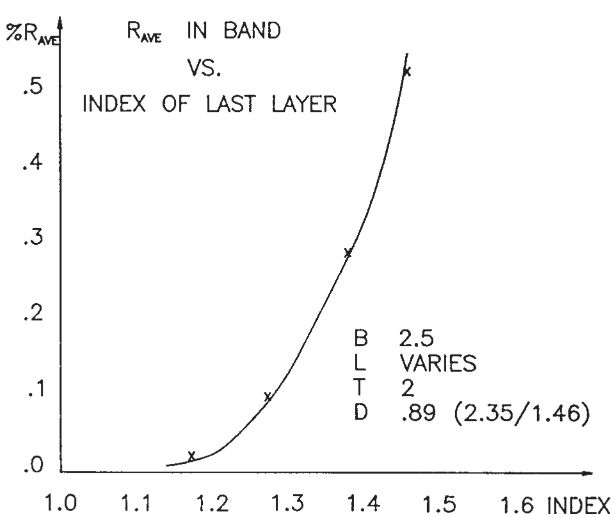

FIG. 4. AVERAGE REFLECTANCE IN BAND VERSUS REFRACTIVE INDEX OF LAST LAYER. CURVE IS FROM FORMULA, X'S ARE FROM EMPIRICAL DATA.

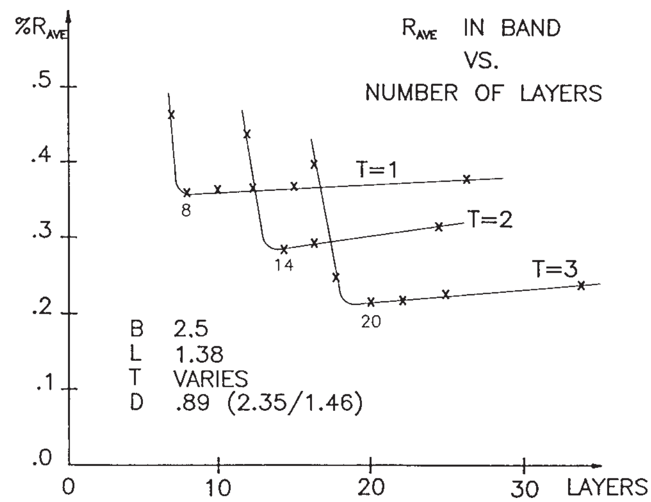

FIG. 5. AVERAGE REFLECTANCE IN BAND VERSUS NUMBER OF LAYERS. THIS IMPLIES #=2 +6*T LAYERS. X'S ARE EMPIRICAL POINTS.

Figure 6 shows the influence of the index difference between the high and low indices in the stack. This is separated from the last layer index which is a special case. Another counterintuitive result was that using a greater variety of indices in one coating (more than two) was actually a design disadvantage. Two indices give the lowest R; we use three because of scattering considerations due to the physical properties resulting from our processes.

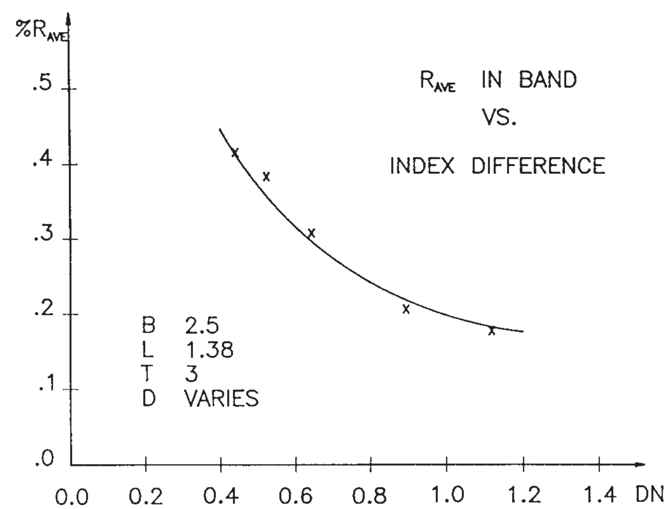

FIG. 6. AVERAGE % REFLECTANCE IN BAND VERSUS INDEX OF REFRACTION DIFFERENCE IN ALL LAYERS EXCEPT LAST. CURVE FROM FORMULA, X'S FROM EMPIRICAL DATA

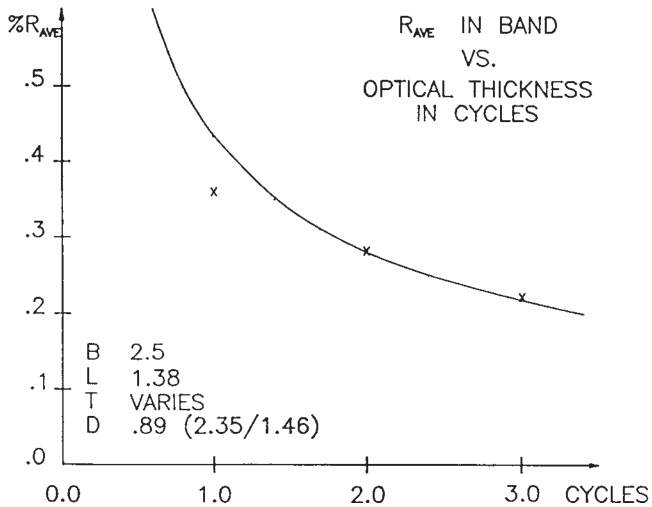

FIG. 7. AVERAGE REFLECTANCE IN BAND VERSUS OPTICAL THICKNESS IN CYCLES OR WAVES AT LONGEST WAVELENGTH OF THE BAND. CURVE IS FROM FORMULA, X'S FROM EMPIRICAL DATA.

Figure 7 shows the effect of overall optical thickness. We have studied this from other points of view also [2], where the effects of extra thickness seemed to have little advantage when any hypothetical indices could be used. The advantage of extra thickness may be in the ability to partially compensate for the lack of the desired very low index last layer. Looking at Fig. 5, one might conclude that about 38 layers and a T of 6 could achieve R=0 for a 2.5x bandwidth. We hope to try this some time, but we do not expect it to work out that well. Also one might expect that if a straight line fit the minima in Fig. 5, a zero thickness coating would have an R of 0.45%. We know this cannot be true, since the bare substrate would reflect 4.2% for a normal crown glass. We have therefore chosen a reciprocal function to partially accomodate these expectations and have the estimated value rise to near an appropriate 1.2% for a single .25 wave layer and asymptotically approach zero for very thick designs. Further investigation is needed in this area.

The influence of the substrate index was found to be almost negligible in the cases studied. This is not true for $T<0.5$, but for $T>1$ the previous studies [1] show that the index profiles first rise to a level higher than that of the substrate before falling toward 1.0. Therefore the starting index has little or no effect on the final results.

SUMMARY

We have empirically derived a formula to allow the estimation of the minimum average reflectance of very broadband AR coatings in the visble and near infrared region. The variables with major effects on the results are bandwidth, lowest available index, overall optical thickness, index difference from high to low, and the number of layers into which the overall thickness is divided. We found that substrate index was not a significant factor and that intermediate indices between the high and low indices available were a disadvantage. These two findings were somewhat unexpected.

The formula can be used to accurately predict the best performance that can be expected of a design of homogeneous layers for a given set of materials. The "ideal" number of layers in a design for a given thickness can also be predicted.

We expect this to be a useful tool for engineers and designers, and we hope to extend the ranges of applicabilty in the future.

REFERENCES

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