Estimating the Reflection Losses in the Passband of Edge Filters

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ABSTRACT

Edge filters which block one spectral region and pass an adjacent region are normally constructed with periodic stacks of high and low index layers of equal quarter wave optical thickness at the center wavelength of the blocked band. A preliminary and a subsequent aperiodic structure of several layers which minimize the reflectance in the passband are usually needed to transition from the effective index of the substrate to the effective index of the periodic structure and from the structure to the final medium. This paper addresses the estimation of the possibilities and limitations of these antireflection or matching layers to reduce the reflections before the coating is actually designed. Equations are given for the estimation of the average reflectance in the passband as a function of the number of layers and the width of the passband for both short and long wavelength pass filters and for passbands on both sides of a “minus filter”.

INTRODUCTION

In our previous work[1] on estimating the results to be expected before designing antireflection (AR) coatings, we used linear wavelength plots and bandwidths were defined as the ratio of the longest to the shortest wavelengths of the AR band. When we went to study the passbands on either side of a block band which creates an edge filter, it appears more rational to use linear frequency or wavenumbers (cm^{-1}) for the plots and the definition of bandwidth. This is true for the current work and possibly for the previous work. Figure 1 shows a short wavelength pass (SWP) filter on a linear wavelength scale and Figure 2 shows the same design on a linear frequency or wavenumber scale which exhibits more symmetry in simple design cases. The design of Figures 1 and 2 is (.5L 1H .5L)10 where L is a layer with an index of refraction 1.46 and H is a layer of index 2.2. The thickness of the layers are in units of quarter wave optical thickness (QWOT) at the center wavelength or frequency of the first order blocking band. The substrates are of index 1.52 and the medium on the other side of the stack is of index 1.0. Dispersion and absorption are not included in this study. All of the present work considers equal optical thickness of the H and L layers within the periodic stack.

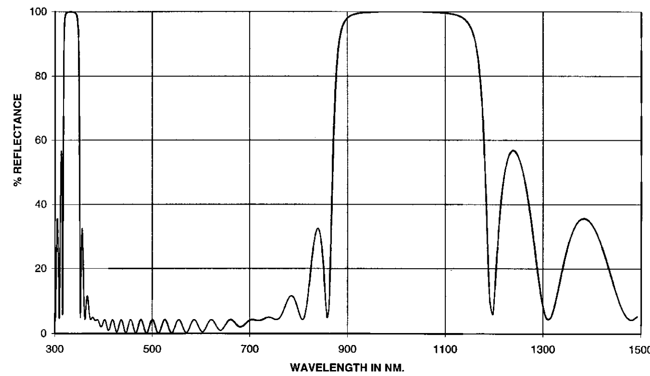

Figure 1. Short wavelength pass (SWP) filter on a linear wavelength scale.

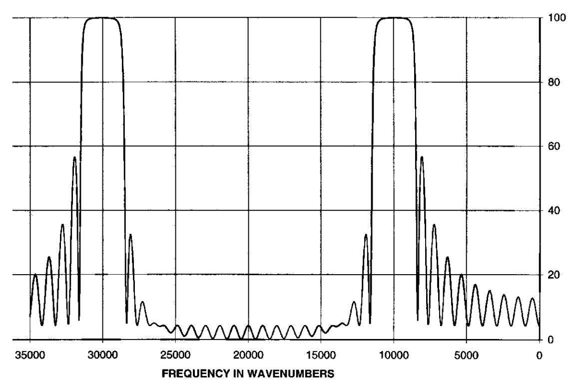

Figure 2. Short wavelength pass (SWP) filter on a linear frequency or wavenumber (cm^{-1}) scale.

The design of Figures 1 and 2 is a good starting place for a SWP filter as it already has relatively low reflectance over the broad passband. The design of Figure 3, which is (.5H 1L .5H)10, is a good starting place for a long wavelength pass (LWP) filter for the same reason. We will now define the bandwidth of the AR as the fraction of the frequency range from zero frequency to the center of the blocking band. By examination of Figures 2 and 3, we can see that the AR bandwidth of a LWP filter in these cases is limited to a maximum of about 0.8 by the distance from zero frequency to the of the edge of the block band. The SWP is limited to about twice that of the LWP, or 1.6, before the edge of the third order block band created by the stack is reached.

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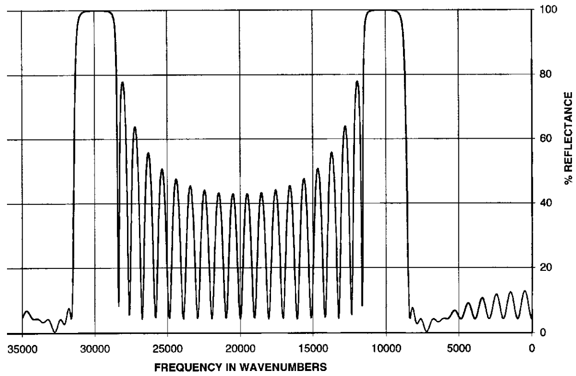

Figure 3. Long wavelength pass (LWP) filter on a linear frequency scale.

A series of design optimizations were performed on AR coatings or "matching layers" on the substrate and "air" sides of the blocking stack to match the stack to the medium on that side of the stack. The total number of AR layers in these coatings varied from 0 to 19 in. The bandwidth was sampled at 0.2, 0.4, 0.8 and, in the SWP and BWP cases, at 1.6. The number of additional layers on one side of the stack was equal to that of the other side to within one (1) layer in each case; such as 2 and 1, 2 and 3, 4 and 3, 4 and 5, etc. The layers next to the substrate were always H because an L layer would have little effect due to the small refractive index difference from the substrate. Similarly, the last layer before the medium of index 1.0 was always L because that gives better AR properties than a last layer of H.

Figure 4 shows the results of a LWP design where the bandwidth was 0.8 and the total number of additional layers was 19. This is an extreme case where the point of diminishing returns on the number of layers has been exceeded. It does, however, illustrate a practical limit on what can be done with this type of design at the maximum LWP bandwidth. Figure 5 shows a SWP design for the maximum bandwidth using 11 additional layers. When we designed for one half of the maximum SWP bandwidth (0.8), we achieve what is seen in Figure 6. The rest of the samples over the ranges were of this same nature.

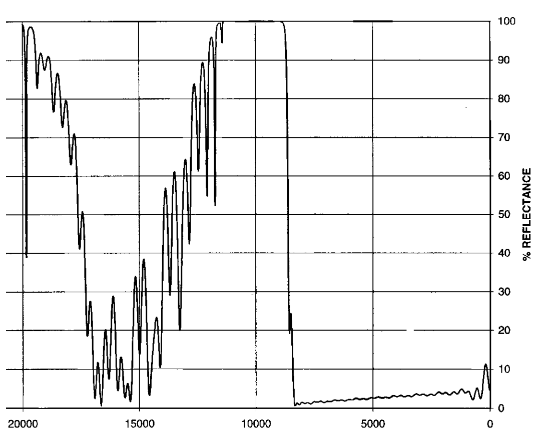

Figure 4. Results of a LWP design where the bandwidth was 0.8 and the total number of additional layers was 19.

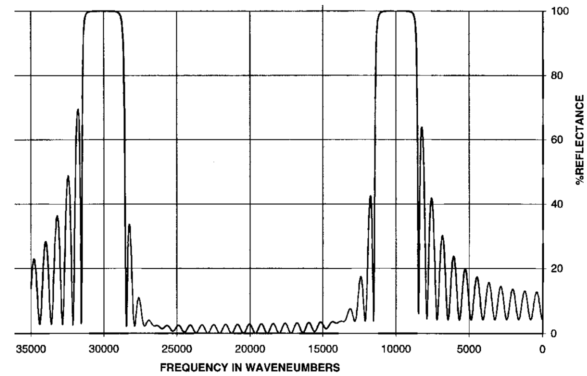

Figure 5. SWP design for the 1.6 maximum bandwidth using 11 additional AR layers.

Our previous work[1] included the effects of the index difference between the L and H materials and also the effect of the index of the last layer of an AR design. It is often possible to lower the average reflection of a LWP AR band even further if a last layer has a yet lower index. This might typically be of index 1.38 or less, and it could reduce the result by approximately 1/5 to 1/4 of the result using just L at 1.46. However, we have not added these two additional variables in an effort to keep the results more straightforward. The general effect of these other two variables was covered in the previous work. It is also appropriate to note that the LWP part of this study is consistent with the earlier work where consideration of a block band was not included. However, a block band was in fact present at a wavelengths less than (wavenumbers greater than) the AR band even though the block band was ignored.

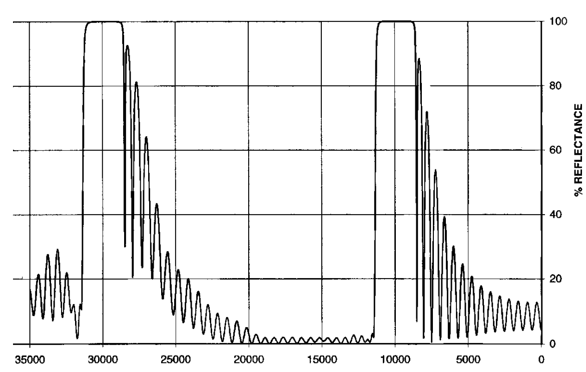

Figure 6. SWP designed for half (0.8) of the maximum bandwidth using 11 additional AR layers.

It can be seen in Figures 1 through 6 that the spectral region on the opposite spectral side of the block band from the AR will generally have high uncontrolled reflections. Thelen[2] did extensive work with "minus filters" where the ideal case would be a block band with no reflection on either side of the block band (LWP and SWP). This creates an even greater challenge, particularly if the AR bands are broad. We extended our design study to include this case which we will call a both long and short wavelength pass (BWP) filter. For simplicity in this part of the study, we always set the bandwidth on the SWP side of the BWP filter to two (2) times that of the LWP side. This would not generally have to be the case, but without such a limitation to this study the range of possibilities might lead to confusion rather than understanding. In all of these cases, when the reflection is reduced in one region it increases in another (for a given number of layers). It appears that the integral of reflection over all frequencies may be preserved! The goal is to move the unwanted reflections to a region where they do not affect the desired performance. In the case of the BWP with broad AR bands, there is very little place left to send the unwanted reflections. In this case, it becomes mostly an issue of balancing the reflections on both sides to best suit the needs of the problem.

PROCEDURE

A series of design optimizations were performed for each of the SWP, LWP, and BWP cases to find the minimum average reflectance over the band (%Rave) wherein the bandwidths and number of layers were varied over the ranges discussed above. The non-stack AR layers of the designs were varied and optimized using standard thin film design software[3]. This was done with respect to equal target values that were spaced in equal frequency intervals over the bandwidth. The targets were closely spaced to have several target points on each spectral cycle in the result. When an optimum was reached using the "NOL Gradient Methods" of the software[3], the result was reoptimized with the "Levenberg-Marquart" algorithm to see if it could be further optimized. Usually, only small improvements were found.

The resulting %Rave as a function of the two variables (total number of non- stack (AR) layers and bandwidth) was treated as Historical Data using design of experiments (DOE) methodology as described by Schmidt and Launsby[4]. When this collection of data was processed by standard DOE statistical software[5], the results are readily illustrated in the graphic plots shown in Figures 7, 9, and 11 for SWP, LWP, and BWP filters. The software also provides the coefficients for equations to calculate any point on these surfaces that have been statistically fit to the data to the third order including interactions of the variables.

RESULTS

The results of interest in this work are the %Rave over the bandwidth that can be achieved as a function of number of additional layers and bandwidth. Figures 7, 9 and 11 are three dimensional plots of the resulting minimum predicted %Rave versus number of layers and bandwidth for the SWP, LWP, and BWP designs. This analysis allows us to generate the following equations to estimate the minimum %Rave to be expected as a function of the number of layers, N, and the bandwidth, B:

$$\%Rave\ (SWP) = 4.1204 - 2.1195N + .0607B + .2685NB + .3575N^2 - .0204N^3$$

$$\%Rave\ (LWP) = 3.9821 - 1.50447N + .0158B + .19131N^2 + 4.4486B^2 - .0082N^3$$

$$\%Rave\ (BWP) = 8.71509 - 2.17882N + 15.907B + .16413N^2 - .00409N^3 + .3327NB - 15.38B^2$$

These equations are approximations and will generate some small negative values for large N and small B, but these can be taken to mean near zero values for Rave. A spreadsheet can be easily set up to take the input of N and B and display the predicted %Rave.

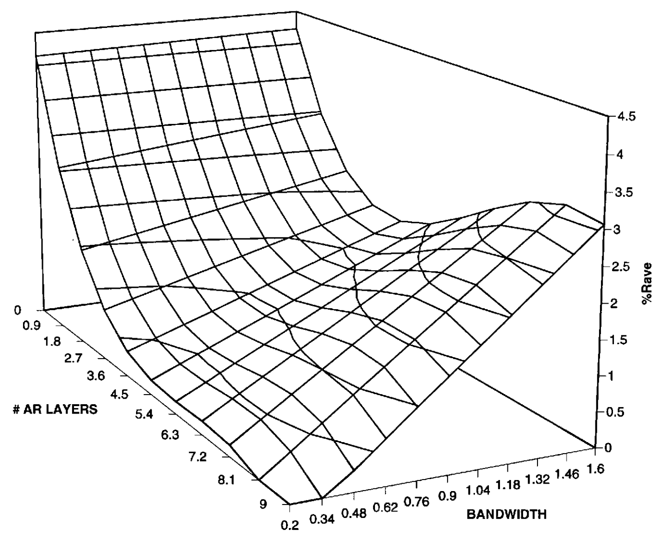

Figure 7. Three dimensional plot of the resulting minimum predicted %Rave versus number of AR layers and bandwidth for the SWP filters.

In Figures 8 and 10, we can see the %Rave from the individual detail designs versus number of AR layers as solid lines for the different bandwidths. After a total of about 5 AR layers in the SWP case of Figure 8, there is no significant improvement in the %Rave. The LWP case is slightly more gradual, but reaches a point of diminishing returns at total of about 9 AR layers. As a result of this observation, the raw data from 0 to 9 layers is all that was included in the statistical fitting processes that generated Figures 7 and 9. The dotted lines in Figures 8 and 10 show the values predicted by the above equations for different bandwidths for comparison with the design values. Figure 8 shows a reasonably useful fit out to 5 AR layers where the real changes with additional layers become insignificant. The reader should, however, keep the accuracy limitations of the filters prediction in mind, particularly for the larger bandwidths. Figure 10 shows even better agreement for the LWP cases. For practical purposes, if N is greater than 9, the %Rave can be taken as the same as for N equal to 9.

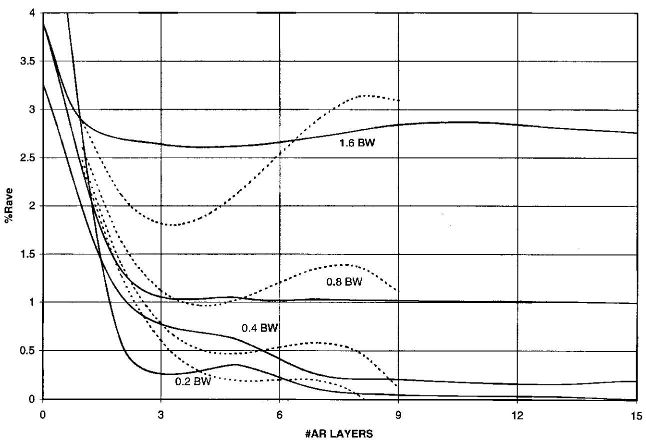

Figure 8. Solid lines are %Rave for SWP filters from the individual detail designs versus layers and bandwidth. The dotted lines are the values predicted by the equations.

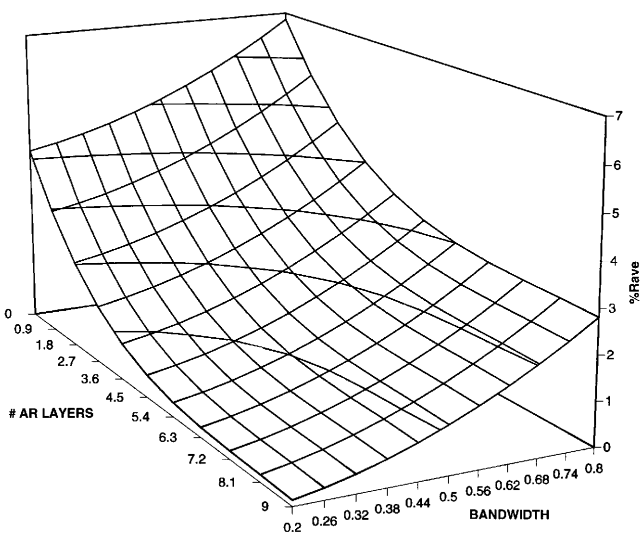

Figure 9. Three dimensional plot of the resulting minimum predicted %Rave versus number of AR layers and bandwidth for the LWP filters.

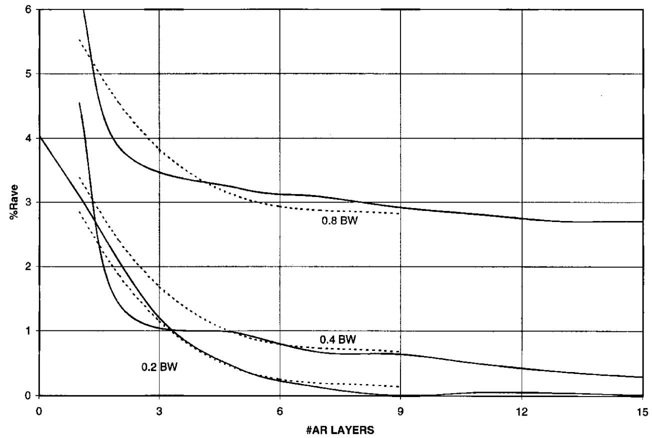

Figure 10. Solid lines are %Rave for LWP filters from the individual detail designs versus layers and bandwidth. The dotted lines are the values predicted by the equations.

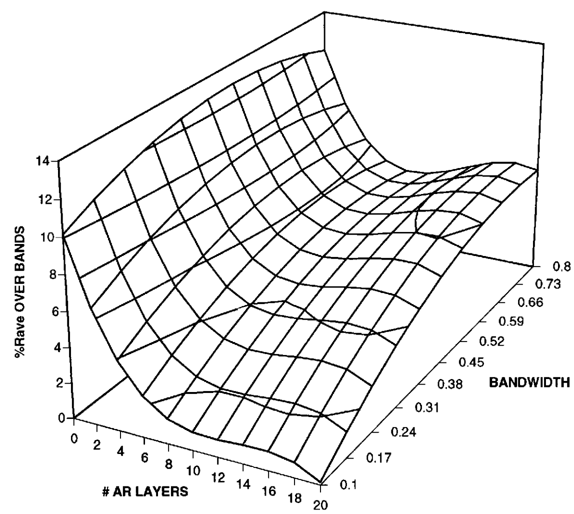

Figure 11. Three dimensional plot of the resulting minimum predicted %Rave versus number of AR layers and bandwidth for the BWP filters.

CONCLUSIONS

It is not a surprise to find again that the minimum average reflectance that can be achieved in a passband increases with bandwidth and decreases with numbers of AR layers. However, it is somewhat more surprising to see, in the SWP cases of Figures 7 and 8, that a total of about five (5) AR layers or less seems to be the point of diminishing returns in all cases for all bandwidths in the range. From Figures 9 through 11 for LWP and BWP, we see that a total of 9 or 10 layers (or about five (5) per interface) seem to be the point of diminishing returns. These results are also consistent with other experience where we know that two layers should allow a perfect AR at most interfaces if the bandwidth is narrow enough, namely a "V-coat". The results of this work now allow us to make precalculations of the %Rave which can be expected in the passband of edge and minus filters when using the common materials like SiO_2 and TiO_2 on crown glass.

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