Search for the Cause of Asymmetric Results of Monitoring Errors in DWDM Filters and the Benefits of Corrections in the Last Two Layers

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Key Words: Monitoring; Narrow band filter coatings; Film thickness monitors; Error correction

ABSTRACT

In previous reports on the sensitivity to layer thickness errors of DWDM and similar narrow band filter coatings, it was noted that the effect of monitoring errors that occur before the turning point appear more severe than those that occur after it. No satisfactory explanation had been found for this result. We report on the search for the explanation of that and related findings. The previous simulations did not deal with final corrections that might be made in the last two antireflection layers in the deposition of the design. We now also simulate those final layer adjustments, show how they might be done, and show the benefits that may be obtained.

INTRODUCTION

We have previously reported [1-4] on the simulation of errors in the optical monitoring termination of layers at their design thicknesses and the effects of noise/errors in the monitoring signal. These studies have been for narrow bandpass (NBP) filters such as might be used in telecommunications. The same example filter design as was used before for Dense Wavelength Division Multiplexing (DWDM) is used here, namely: (1H 1L)9 4H (1L 1H)9 1L (1H 1L)9 4H (1L 1H)9 1L (1H 1L)9 4H (1L 1H)8 1L .52072H .86628L. Here, the indices are 2.05 for H and 1.45 for L.

The effects of random errors in layer termination are simulated, with the natural error compensation properties of the commonly used "turning point" (TP) monitoring technique. The three cavity filter design as given above has 114 layers. The common monitoring technique is to terminate each new layer at the TP where the transmittance of the piece being monitored passes through a point of inflection and changes direction. This is normally at a point of integral quarter wave optical thickness (QWOT). If a previous termination was in error before or after the TP, the current layer would be correspondingly thicker or thinner than a QWOT when the layer is terminated at the next TP. When this technique is used, errors from previous layer terminations are largely compensated [1-4], and we have discussed the necessary conditions to take advantage of this effect.

The errors have been simulated as having a random distribution as a percentage of transmittance imposed on the sensing of each TP termination in sequence, and then the next TP was found. Three types of cases were simulated: 1) where the errors are entirely on the short side of the TP (before), 2) where the errors were symmetrically distributed (centered) about the ideal TP, and 3) where the errors extend from the TP to greater thickness (after), as might be more typical of an actual case.

APPARENT ASYMMETRY

In the modeling of errors and compensation effects as previously reported [2], an unexplained asymmetry was observed between errors which occur before and after the ideal turning points for layer termination. Further refinement of the simulation algorithm has shown that the results are in fact symmetric as illustrated in Figures 1–3.

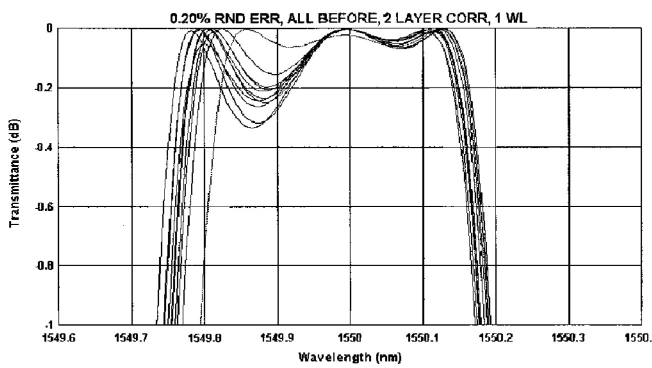

Figure 1: Effects on the filter dB transmittance of random monitoring errors of 0.20% in transmittance at the TP. All of the random errors in this case are before the TP. These curves represent ten simulations with the stated random errors plus a trace of the ideal design spectrum in the background.

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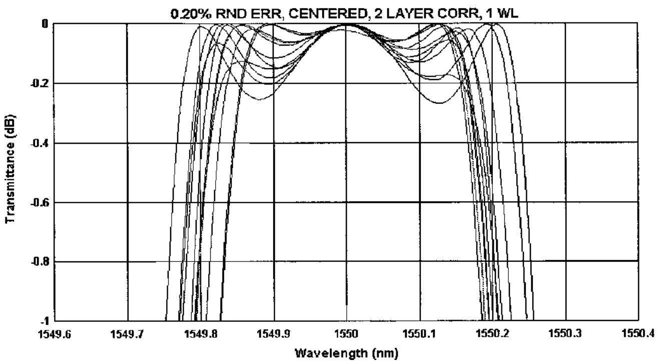

Figure 2: Results similar to Figure 1 where all of the random errors are centered about the TP.

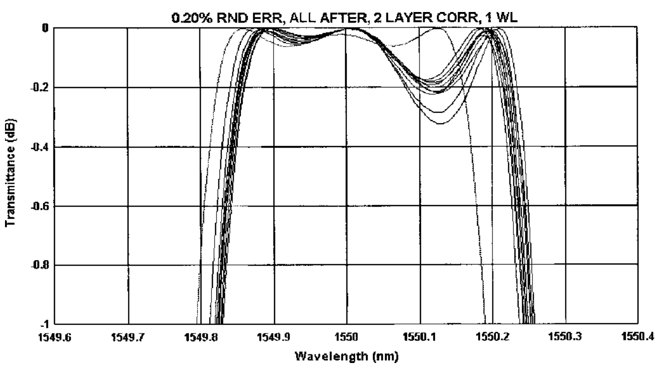

Figure 3: Results similar to Figure 1 where all of the random errors are after the TP.

EFFECTS OF FINAL LAYER MONITORING TECHNIQUES

In the work reported here, we have refined the model to simulate options of how the last two layers might be monitored in actual practice. In the three cases shown in Figures 1–3, the thickness of both of the last two layers were optimized for best transmittance at the design/monitoring wavelength; however, this would be difficult to implement in practice. The next-to-last (NTL) layer (number 113) is not a QWOT and does not pass a TP when monitored at the design wavelength as illustrated in Figure 4. Therefore, something other than the TP monitoring technique must be used, such as a physical thickness technique (crystal monitor) or the "time at rate" technique. The very last layer, which is also not a QWOT, could however be terminated at the TP by an optical monitor to give a maximum of transmittance for the filter at the design/monitoring wavelength. There are several possible ways of terminating these last two layers utilizing the type of monitoring equipment which we assume is commonly employed for DWDM filter production at this time.

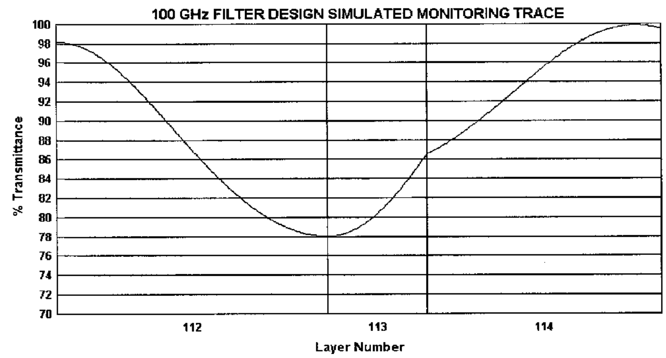

Figure 4: Ideal optical monitor trace at the design wavelength for the last three layers of the design.

From among the variety of ways with which to monitor and control the thickness of the last two layers of such filters, we will deal with the simulation of four types in this paper. Table 1 shows the layer thickness targets of four types of layer termination which will be reviewed. One approach would be to terminate the last two layers at the ideal design thicknesses, independent of the effects of the preceding errors, by a physical thickness control technique as mentioned above. A second technique would be to use the same physical thickness and termination technique for the NTL (113^{th}) layer as above, but terminate the last (114^{th}) layer at the TP by the same optical monitor as used for all of the preceding layers. The third way would be to calculate a predicted thickness for the NTL layer which would provide the highest transmittance for the finished filter, starting from the %R where the 112^{th} layer ended, when the last layer is terminated at the final TP. The fourth possibility is to calculate a predicted thickness for both of the last two layers and use the physical thickness termination technique. The first two of these approaches are already well defined; we will now discuss the third and fourth.

Table 1. Layer thickness targets for the four types of layer termination discussed here.

TYPE	LAYER 113	LAYER 114
1	DESIGN	DESIGN
2	DESIGN	OPTICAL
3	PREDICTED	OPTICAL
4	PREDICTED	PREDICTED

The most readily available information from which to decide the best thickness of the NTL in the third case is the monitor signal transmittance (T) of the filter just before the NTL layer is to be deposited. This T signal has been the basis of all of the layer termination decisions up to that point in the depositions, therefore it is readily available. For purposes of discussion, we will also use the reflectance intensity (R) which is equal to 1-T (because there is no significant absorption involved). The use of R instead of T is partially because it is convenient to illustrate some aspects of the process on a Reflectance Amplitude Diagram (RAD). Figure 5 is a section of such a RAD, the properties of which are described in detail elsewhere [5]. These RADs are actually the reflectance amplitude (r) whose magnitude is the square root of R, or R = rr*, where r* is the complex conjugate of r. This r and an associated phase angle define a point within the limiting circle of r = 1 on the RAD. On such a diagram, the filter deposition starts on the bare substrate with R of about 4% or 0.04. When the Fresnel reflection coefficient is calculated for a substrate of index 1.5 in air, r is equal to -0.2 or a magnitude of 0.2 and phase angle of 180°. This is 1/5th of the way from the origin of coordinates to the bounding circle (r = 1.0) to the left of the center on negative the real axis.

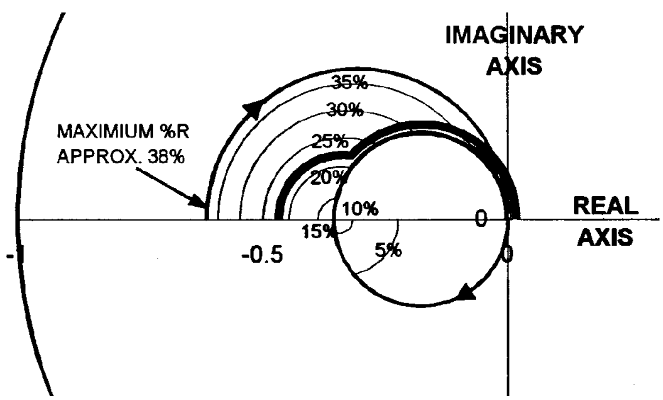

Figure 5: Reflectance amplitude diagram of the range of loci for the last two layers which will provide zero reflectance (100%T) at the design wavelength. Curves are labeled with the %R at the end of the 112th layer and the starting point for the 113th (NTL) layer.

As the first 112 layers of this design are deposited, the r point moves clockwise on semicircles which would each ideally end on the horizontal real axis of the RAD. At the end of the 112th layer, the r point, in most cases, would be in the vicinity of r equal to –0.4 to –0.5 or %R equal to 16 to 25%. In Figure 5, the ideal starting point would be at the left end of the bold set of partial circles. There is a much greater range of "correctable" r points for the end of layer 112 which are encompassed by the largest partial circle in Figure 5. This circle is labeled "Maximum %R Approx. 38%" and the minimum %R would be 0%. However, the examples shown in this paper have almost all been in the range of about 19-25%R. Because the goal is to have terminated layer 112 right at the TP, the r of its end point should be on the real axis except for the influence of the small phase angle errors which would cause it to fall a little before (below) the negative real axis or a little above (after) it. Therefore, the salient feature to use in our calculation/decision is the magnitude of r which we can measured by R (or 1-T). The small phase errors from the nominal 180° can be ignored per the above discussion.

In examining Figure 5, we see that the locus of a typical last two layer pair moves on the high index material circle clockwise from the starting point near the negative real axis until it intersects and transfers to the low index material circle which then passes through the origin where r and %R equal zero. In the unlikely case where the starting R is less than 12.6%, the locus of the high index layer starts by moving downward until it intersects the low index path to the origin. For the special case of R equal to 12.6%, no high index layer is required. However, any thickness of H could be used because the high index locus would only stay at that same spot, since it is the center for all of the H circles.

The thicknesses of high and low index layers required to move from a given %R to zero reflectance at the origin are plotted in Figures 6 and 7. It can be seen that over a region broader than might be of practical interest (15–30%), both of these are well approximated by a linear function of %R at the end of layer 112 (illustrated by the thin straight lines). Therefore, we can use the linear equations shown on each figure with confidence to predict the high and low index layer thicknesses needed to bring the reflectance to zero at the design wavelength. Even in the region around 12.6%R, the linearly predicted high index thickness can be shown to work well because of the insensitivity mentioned above.

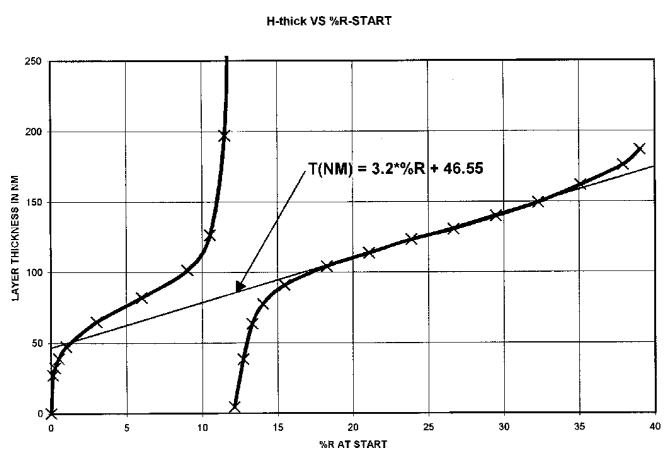

Figure 6: Ideal thickness for the high index NTL layer versus %R at the start of the layer to produce (with the last layer) no reflection loss at the design/monitoring wavelength**.**

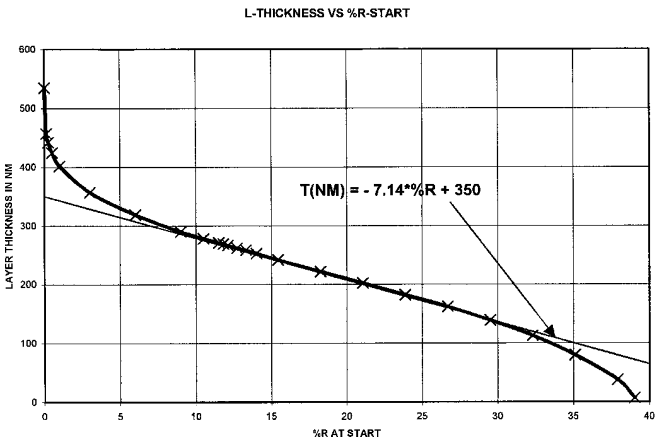

Figure 7: Ideal thickness for the last low index layer versus %R at the start of the layer to produce (with the NTL layer) no reflection loss at the design/monitoring wavelength.

We will now compare the spectral results of using these four different approaches in Figures 8 through 11. Figure 8 is the case where *both* of the last two layers are terminated at the ideal *design* thicknesses by physical rather than optical monitoring. These two layers are simulated with no random errors, since they would not be expected to significantly influence the results. Whether a crystal monitor or time and rate were used, we would calibrate those thicknesses based on the crystal readings or time and rates from the previous few layers of the same materials. This seems to give a good result in general over the passband, although the transmittance is not maximum in all cases at the design/monitoring wavelength. Figure 9 uses the *design* thickness for the high index NTL terminated physically as in Figure 8, but the last layer is *optically* terminated at the TP using the monitoring wavelength. This somewhat improves the losses at the monitoring wavelength. This may be the technique which is commonly used by current producers. Figure 10 uses the *predicted* thickness for the high index NTL layer per the equation given in Figure 6; the last layer is the *optically* terminated at the monitoring wavelength. This is seen to minimize the losses at the monitoring wavelength as compared to the first two approaches, but somewhat at the expense of other wavelengths in the passband. Figure 11 uses the *predicted* thicknesses per the equations for both layers and terminates them physically as in the first case of Figure 8. This technique is almost as easy to accomplish as the first scheme of Figure 8, and it produces a result which is not significantly different from the third case of Figure 10. It can be seen that the losses at the monitoring wavelength can be reduced by the correct choice of approach, but that this (somewhat surprisingly) may not lead to the best overall result in the passband. We are not aware of any use of the approach shown in Figure 10. Also to our surprise, the approaches seen in Figures 8 and 11, which use no optimization by terminating at the TP of the last layer, show the best results for the overall passband in the Figure 8 case or the monitor wavelength in the Figure 11 case.

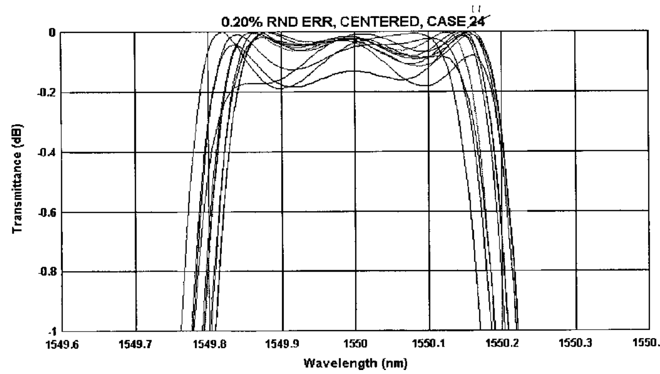

Figure 8: Ten cases where *both* of the last two layers are terminated at the ideal *design* thicknesses by physical rather than optical monitoring.

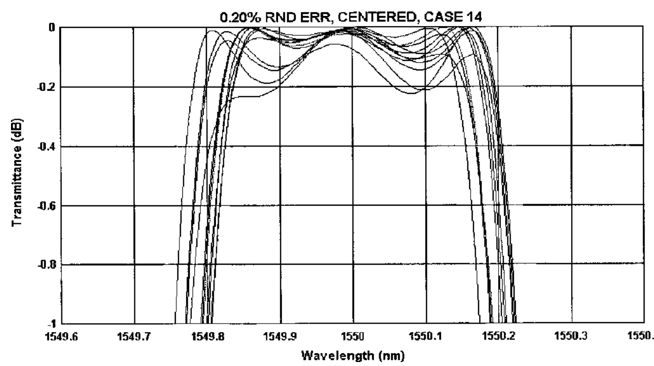

Figure 9: Ten cases where the *design* thickness for the high index NTL is terminated physically as in Figure 8, but the last layer is terminated *optically* at the TP using the monitoring wavelength.

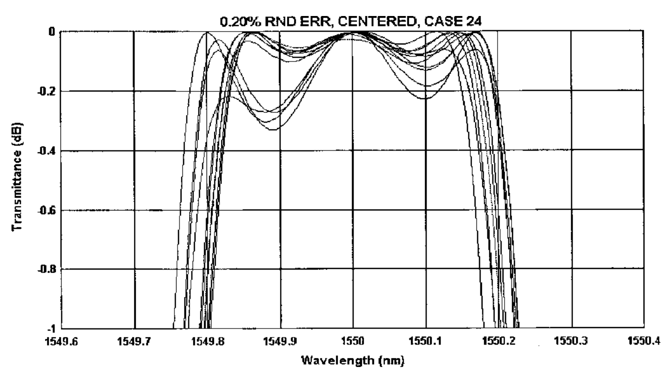

Figure 10: Ten cases where the *predicted* thickness is used for the high index NTL layer per the equation given in Figure 6, and the last layer is the *optically* terminated at the TP using the monitoring wavelength.

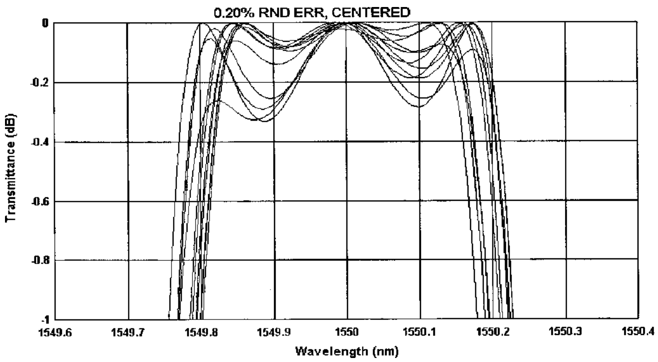

Figure 11: Ten cases where the *predicted* thicknesses are used for *both* layers which are terminated physically as in the first case of Figure 8.

CONCLUSIONS

The effect of turning point monitoring errors on the yield and performance of NBP filters has been simulated to a further refined degree. The previously observed asymmetry with respect to the effect of errors before and after the turning points have been shown to be an algorithm artifact which has been eliminated. Four approaches to the monitoring of the final two layers of a design have been compared. It has been found that optimizing the performance at the monitoring wavelength may be somewhat detrimental to desired performance in the passband. We conclude, as an ancillary benefit of examining these results, that the random errors in %T at the turning points can be on the order of 0.20% or possibly greater, depending on the monitoring approach used for the last two layers of the design. This should allow one to obtain a reasonable yield for such a 100 GHz DWDM filter with a 0.3 dB specification on losses in the passband.

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REFERENCES

1. R. R. Willey, "Achieving Narrow Bandpass Filters Which Meet the Performance Required for DWDM," *Thin Solid Films*, 398-399, 1, 2001.

2. R. R. Willey, "Simulation of errors in monitoring narrow bandpass filters," *Appl. Opt.* 41, 3193-3195, 2002.

3. R. R. Willey, "Estimating the Properties of DWDM Filters Before Designing and Their Error Sensitivity and Compensation Effects in Production," *44th Annual Technical Conference Proceedings of the Society of Vacuum Coaters*, 262 ,2001.

4. R. R. Willey, "Application of a refined error model of turning point monitoring to the simulation of narrow bandpass filter production," *45th Annual Technical Conference Proceedings of the Society of Vacuum Coaters*, 295 ,2002.

5. R. R. Willey, *Practical Design and Production of Optical Thin Films*, 2nd Ed., page 8 and following, Marcel Dekker, Inc., 2002.

6. FilmStar Design Program, FTG Software Associates, P.O. Box 579, Princeton, NJ 08542.