

Design and monitoring of narrow bandpass filters composed of non-quarter-wave thicknesses

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ABSTRACT

Narrow bandpass filters have historically been designs of quarter waves at the passband wavelength, and have been monitored at the turning points using the passband wavelength. By direct monitoring at the passband wavelength, errors have been shown to be primarily self compensated, and have allowed much better performance than could otherwise be expected. The turning points are difficult to detect precisely and accurately because the change in transmittance with thickness becomes zero at the desired termination point. By proper design with non-quarter-wave layers, essentially the same spectral performance can be achieved by layer terminations that are far enough from turning points to be significantly more sensitive termination points. The design approach is to maintain the optical thickness of the reflector layer pairs at one half-wave of the passband wavelength, but change the ratio of the optical thicknesses of the high and low index layers. These can be adjusted enough so that the thicker layers contain two turning points and the last turning point in the layer can be more accurately and precisely determined. The error compensation benefit from the historic method should be maintained. This leads to potentially improved control during deposition and monitoring of narrow bandpass filters.

Keywords: thin film design, narrow bandpass filters, non-quarter-wave thickness, optical monitoring, error compensation

1. INTRODUCTION

The conventional narrow bandpass filter (NBP) of one cavity is composed of four or five elements. The first element is a **mirror** made by a stack of high and low index layers, each of which are of one quarter wave optical thickness (QWOT) at the design wavelength which is the passband of the NBP. The second element is a **spacer** layer which is one or more *pairs* of QWOT layers of the same index, which therefore comprise a half wave of optical thickness (HWOT) at the passband wavelength. The third element is another **mirror** stack of QWOTs like the first. The fourth element is two or more high and low index layers which are not QWOTs and which provide an **antireflection** (AR) coating for the ensemble of layers at the design wavelength. Referring to the mirror, spacer, and second mirror combination as a *cavity*, it is possible to put two or more cavities in sequence to form a filter with steeper edges and more blocking of flux outside of the passband. Multiple cavities must be separated by a **coupler** layer which is a fifth element, and it is another QWOT that serves to maintain the proper phase relationship between the cavities.

Figure 1 shows the spectral result of the conventional NBP design and Fig. 2 shows the entire predicted optical monitoring trace at 550 nm, which is in the middle of the passband. This design is: Substrate (1H 1L)³ 4H (1L 1H)³ 1L (1H 1L)³ 4H (1L 1H)³ 1L (1H 1L)³ 4H (1L 1H)² 1L 1.24323H 1.37656L Air at 550 nm, where L = 1.46 and H = 2.35 on a substrate of index 1.46. This design would be referred to as a 2:1 design wherein the ratio of the overall optical thickness of a layer pair in the mirror stack to its thinnest element is 2:1. As seen in Fig. 2, each layer would be terminated at the turning point (TP) where the vertical direction of movement of the trace with thickness is about to change as material is being deposited. At such a TP, the change of transmittance with thickness goes to zero; this makes the exact TP difficult to detect and thereby subject to error. All of the layers are terminated at turning points except the (two) coupler layers and the last two or more antireflection (AR) layers which would likely be terminated by quartz micro balance (QMB) or by time-power techniques. Figure 3 further illustrates the monitor trace detail. Points A and B are TPs where the rate of change of the reflectance or transmittance with film thickness goes through zero. Figure 4 shows how it would be difficult to determine the precise position of these TPs in the presence of noise on the trace.

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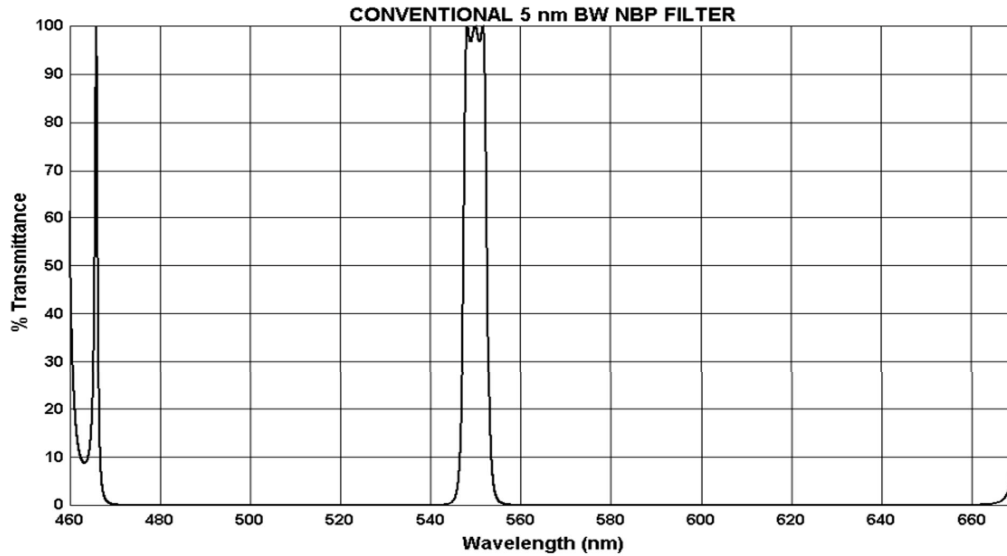


Fig. 1. Spectrum of a conventional NBP filter.

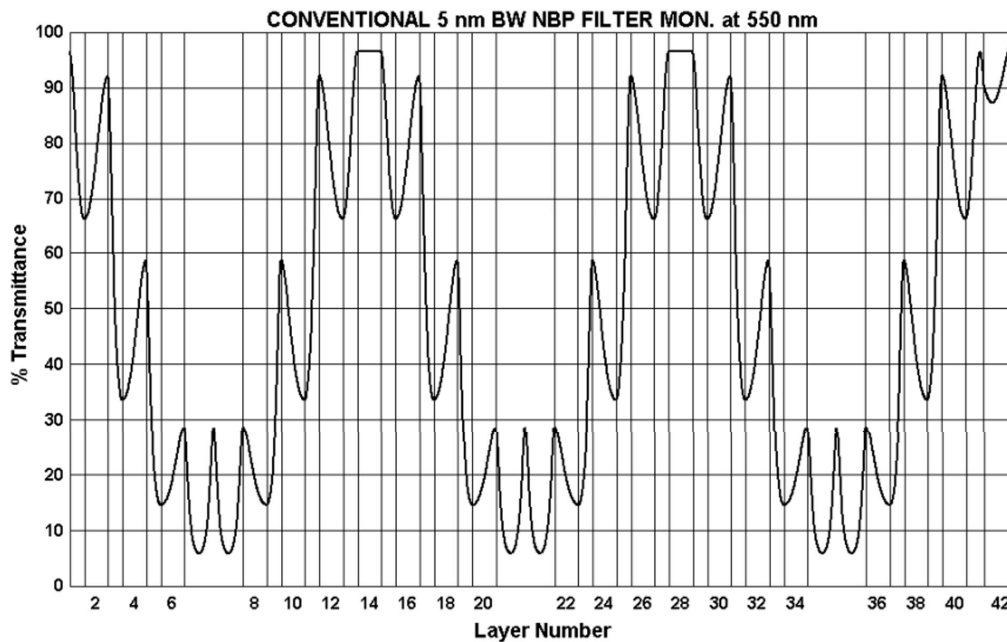


Fig. 2. Predicted optical monitor plot at 550 nm of all 42 layers of Fig. 1.

The subject of this paper is to introduce a modification of the conventional/historic approach to the design and monitoring of NBP filters which should increase the precision of the layer terminations and thereby the performance and yield of the filters produced. This is an extension of the work previously reported [1,2,3] on fence post designs in general and more recently[4] on NBP in particular.

The advantages of monitoring can be gained in a nearly conventional NBP design by selecting a ratio which is greater than the conventional 2:1 in order to shift the layer termination points away from the turning points. The example of a 2.67:1 design is illustrated below. The closer the ratio is to 2:1, the closer will be the blocking band widths and optical density in those bands to that of the 2:1 design, but the termination points will also be closer to the turning points.

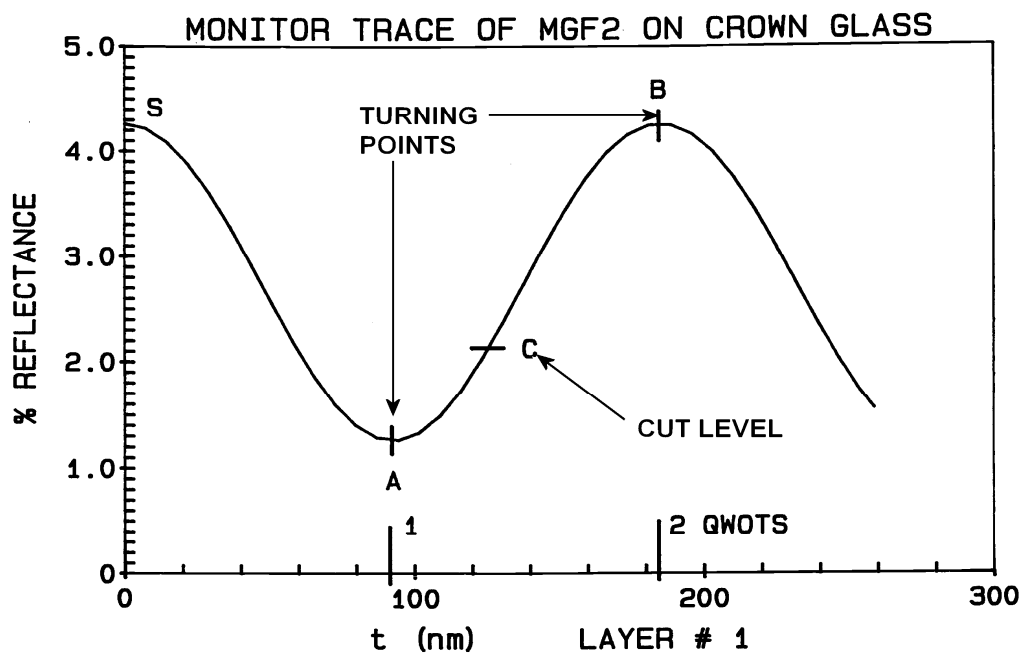


Fig. 3. Single wavelength optical monitor trace versus thickness of the depositing material.

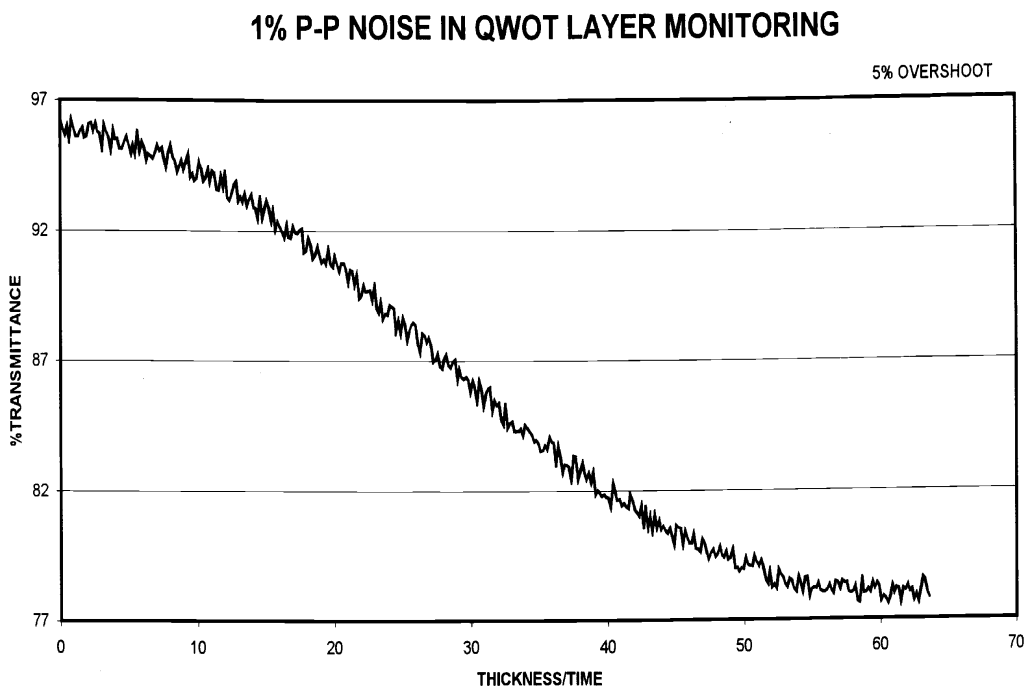


Fig. 4. Effect of noise on the monitoring signal and the difficulty in finding the turning point.

This 44 layer design is: Substrate (1.25H .75L)³ 4.27H (.75L 1.25H)³ .86L (1.25H .75L)³ 4.27H (.75L 1.25H)³ .86L (1.25H .75L)³ 4.27H (.75L 1.25H)³ 1.4776L .16012H 1.38443L Air, with the same materials as above. Figure 5 shows the spectral plot which is very similar to that of Fig. 1. Figure 6 shows the monitoring plot which is very similar to that of Fig. 2.

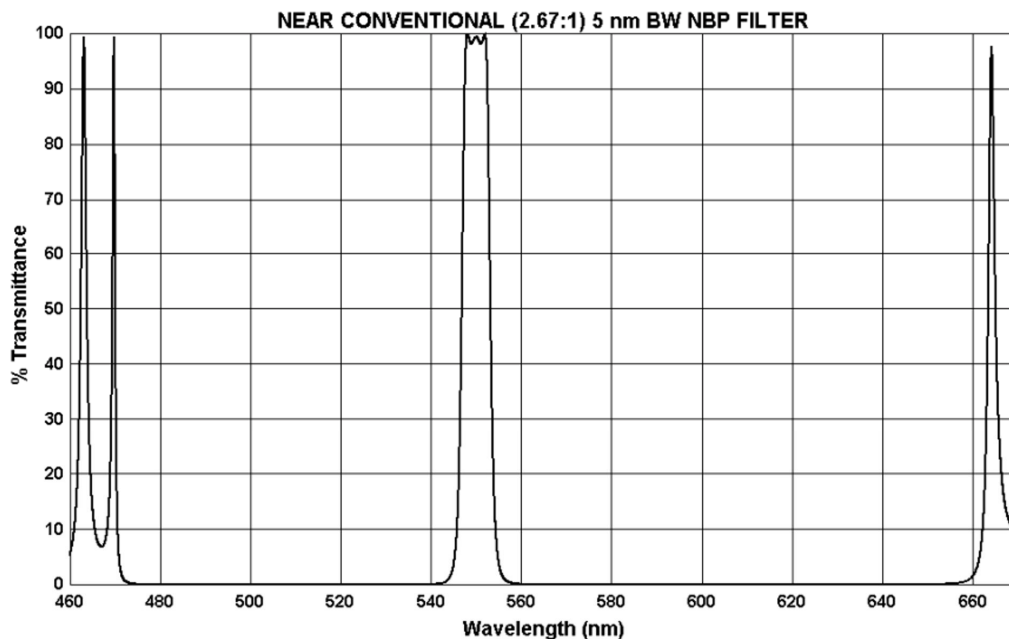


Fig. 5. Spectrum of a nearly conventional NBP filter.

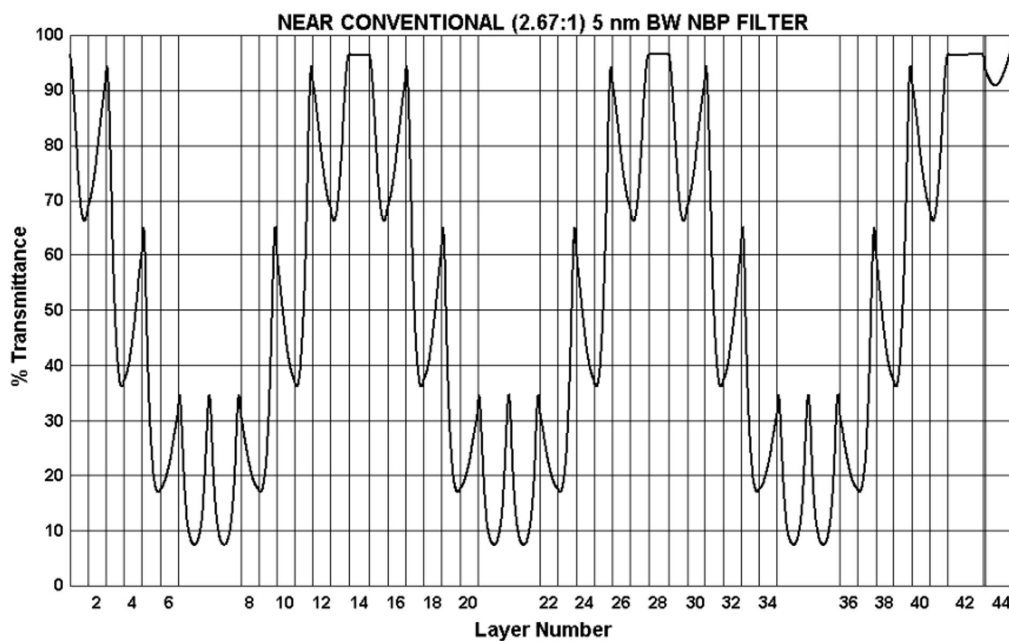


Fig. 6. Predicted optical monitor plot at 550 nm of all 44 layers of Fig. 5.

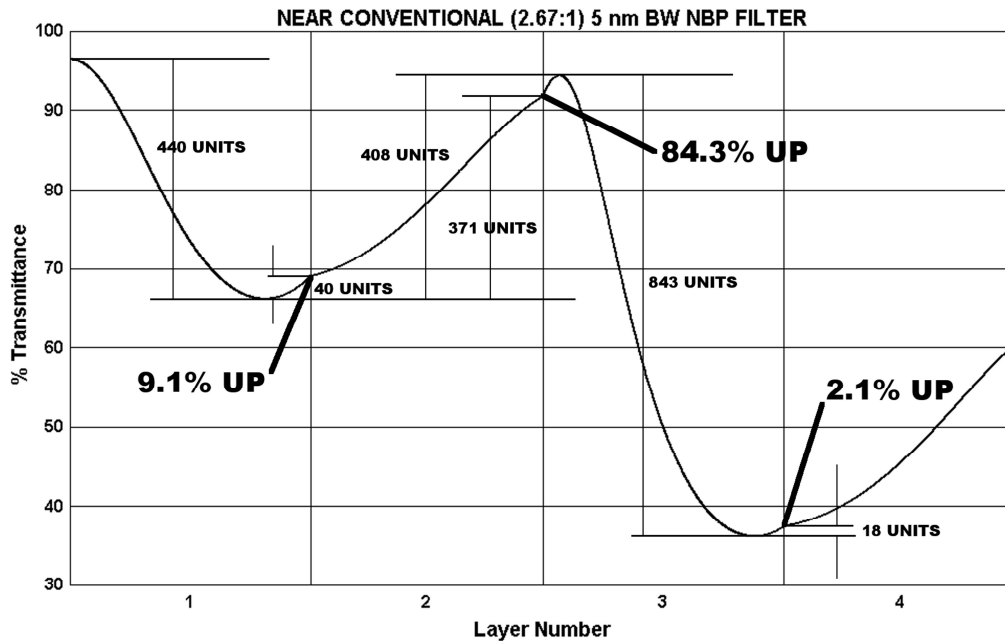


Fig. 7. Optical monitor plot at 550 nm of the first four layers of the Fig. 5 design.

The monitoring of the first four layers is shown in Fig. 7. The first layer is terminated at 9.1% UP from last max-min [5] which includes the start point and first turning point. This has a smaller error probability than terminating at the turning point. The second layer would be terminated at 84.3% UP from these same two max-min points. It would also have less error probability than a turning point termination. The third layer would be terminated at 2.1% UP, etc. This design happens to have the thicker layers as high index, and therefore the max-min's will be in the high index layers. If the low index layers were the thicker ones, the max-min's would be in the low index layers. The actual design choice would depend on other factors such as physical properties, angle sensitivities, etc.

The monitoring shown in Fig. 7 would be vulnerable to problems in past times when the reproducibility of the refractive indices of the layers and the stability of the photometric scale of the optical monitor were much less than they are with modern equipment and processes. Under those circumstances, TP monitoring might be safer. However, with stable deposition processes and photometrics in the optical monitor, the new approach should be better than TP. The advancement of the use of computer programming and control for optical coating systems has made the programming and execution of the new approach much easier than it would be if done manually.

2. DESIGN PROCEDURES

The trade-off to be made in designs for using this non-turning point monitoring is to get the termination points far enough from the turning points (TPs) to gain cut sensitivity, but to keep the changes in bandwidths within acceptable bounds. The passband gets somewhat wider as the ratio of the width of the thinnest layer to the layer pair thickness gets greater. The width of the blocking band gets less with a greater ratio. The pass band can be returned to a narrower value by additional mirror layer pairs or a change of spacer layer thickness[6]; so this is not of great concern. However, the block band width is not as easily changed, and is thus the factor to be most considered in the trade-off.

The procedure which has been used to design a NBP filter for this type of monitoring is as follows: Start with a 3 cavity standard (2:1) NBP with the desired properties and remove all but a single cavity from the design. Set the thicknesses of the H and L layers to the desired ratio and adjust the thickness of the spacer layer by trial and error to center the peak %T

on the design wavelength. Expand the design to three cavities by copying the one cavity design twice with a QWOT coupler layer between each cavity. Adjust the thickness of the coupler layers in tandem to center the peak %T on the design wavelength. Add two (2) AR layers to the substrate interface and three (3) layers to the air side of the design. Optimize these five (5) layers for maximum transmittance in the passband. Adjust the coupler layers as needed to center the results in the passband. Reoptimize the AR layers and adjust the coupler layers until optimum. The addition of two AR layers between the substrate and the NBP stack has shown itself to be particularly beneficial in these non-QWOT NBP designs.

Check the OD in the blocking regions to see that it is satisfactory, and also check the resulting bandwidths for acceptability. Make adjustments as needed to achieve the design goals. Then evaluate the monitoring curves of transmittance versus thickness to see if the termination points look reasonable for the task at hand. If all of these aspects of the design are satisfactory, the remaining task is to establish the monitoring parameters for each layer in terms of the "% Last Max-Min" technique as seen in Figs. 7 and Ref. 5. Note that the thinner layers which have no turning points are still monitored by the "% Last Max-Min" technique using data from the previous layer as seen in layer 2 of Fig. 7 and Ref. 5.

3. GENERAL BEHAVIOR

The behavior of these designs have been surveyed in a range of ratios from 2:1 to 4:1 for this application. The details of the 3.2:1 design will be used here for illustration. The change of the various bandwidths with ratio change will be shown and the % Max-Min for each of the two-turning-point layers in each design.

The design of this NBP is: Sub .15811H .72148L (.625H 1.375L)³ 3.7325H (1.375L .625H)³ 1.168L (.625H 1.375L)³ 3.7325H (1.375L .625H)³ 1.168L (.625H 1.375L)³ 3.7325H (1.375L .625H)³ .2684L .20327H 1.17919L Air. Here L = 1.46, H = 2.35, and the substrate is 1.52. Figures 8 and 9 show the spectral data for this design to compare with Fig. 1 of a similar 2:1 NBP filter.

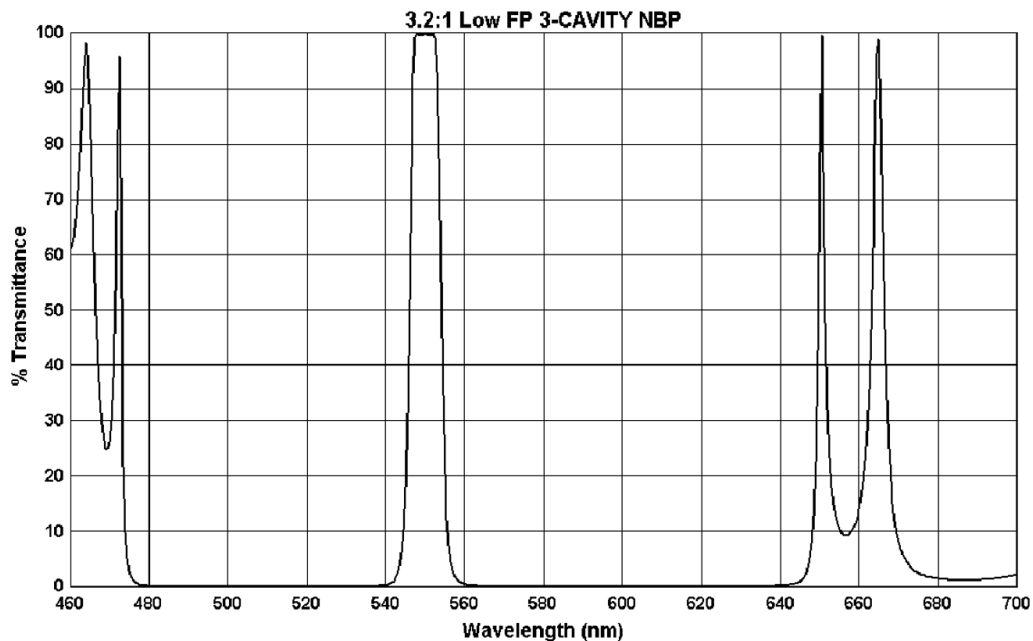


Fig. 8. Spectral plot on % T scale of 3.2:1 ratio design where the low index layers are wide.

This design is only ~20% narrower than the normal 2:1 ratio in the 30db blocking band width, and the db of the peaks of the blocking bands are only ~20% less than the normal 2:1 ratio. The pass bandwidths are ~20% wider than the normal

2:1 ratio design. The full predicted monitoring trace for 550 nm is shown in Fig. 10 compare with Fig. 2 of a similar 2:1 NBP filter. The last cavity is expanded in Fig. 11 for better visibility. The couplers and a few very thin layers might be QMB or time power monitored, but the rest of the layers would be optically monitored. In this case, the even layers, which are the wider low index layers, have two turning points and thereby easy to terminate by the "% Last Max-Min" method. The narrower high index layers are still monitored by the same method, but use the previous turning points for reference.

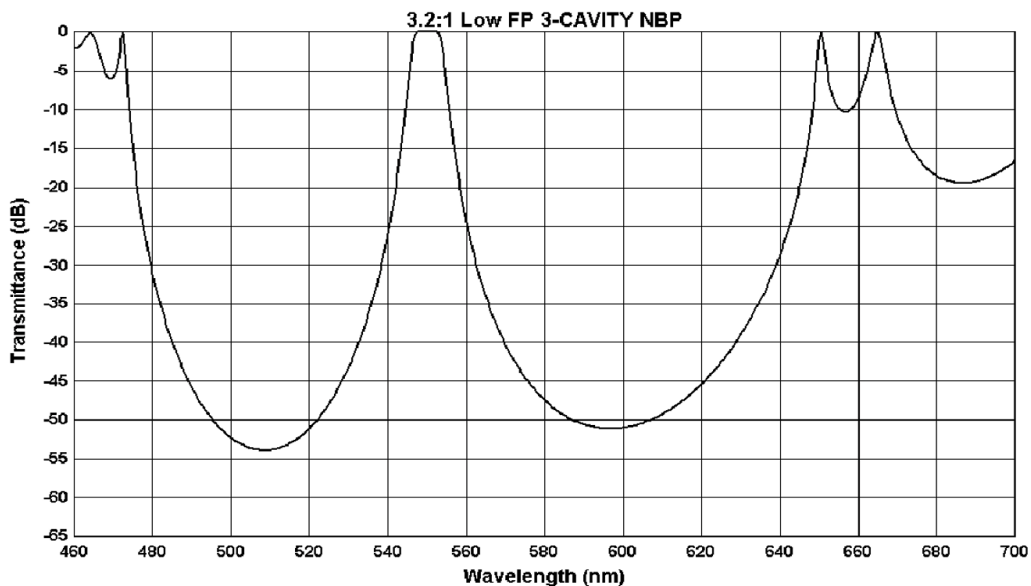


Fig. 9. Spectral plot on T db scale of 3.2:1 ratio design where the low index layers are wide.

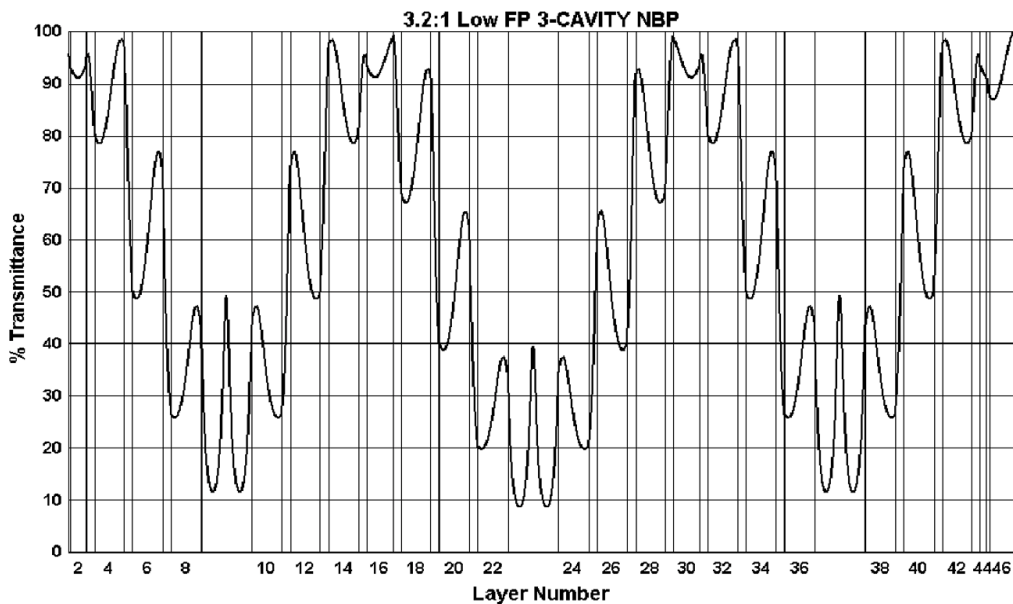


Fig. 10. The full predicted monitoring trace for 550 nm of the 3.2 ratio design.

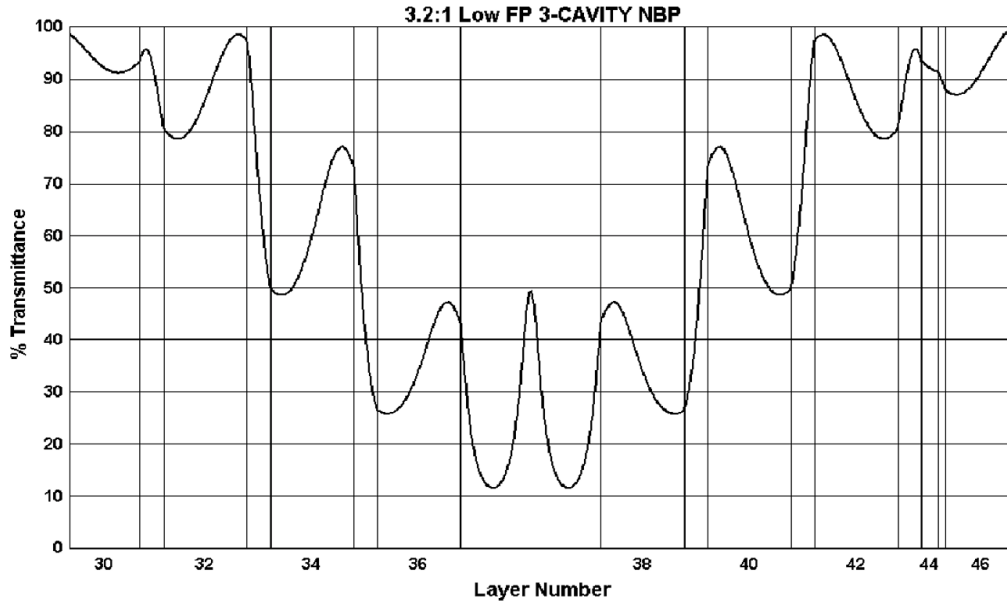


Fig. 11. The last cavity monitoring trace for 550 nm of the 3.2 ratio design expanded.

As described above, designs with ratios of 2:1, 2.67:1, 3.2:1, and 4:1 with both thick low index layers and thick high index layers were made and evaluated for bandwidths, blocking, and %Max-Min termination values in each layer. Results for each of these seven cases is plotted in the next several figures. The difference in the bandwidth and blocking results between the high index and low index thickest layers is seen to be mostly insignificant. Figures 12 through 14 show the influence of the ratio on passband widths at 0.3 and 30 db and the block band width at 30 db.

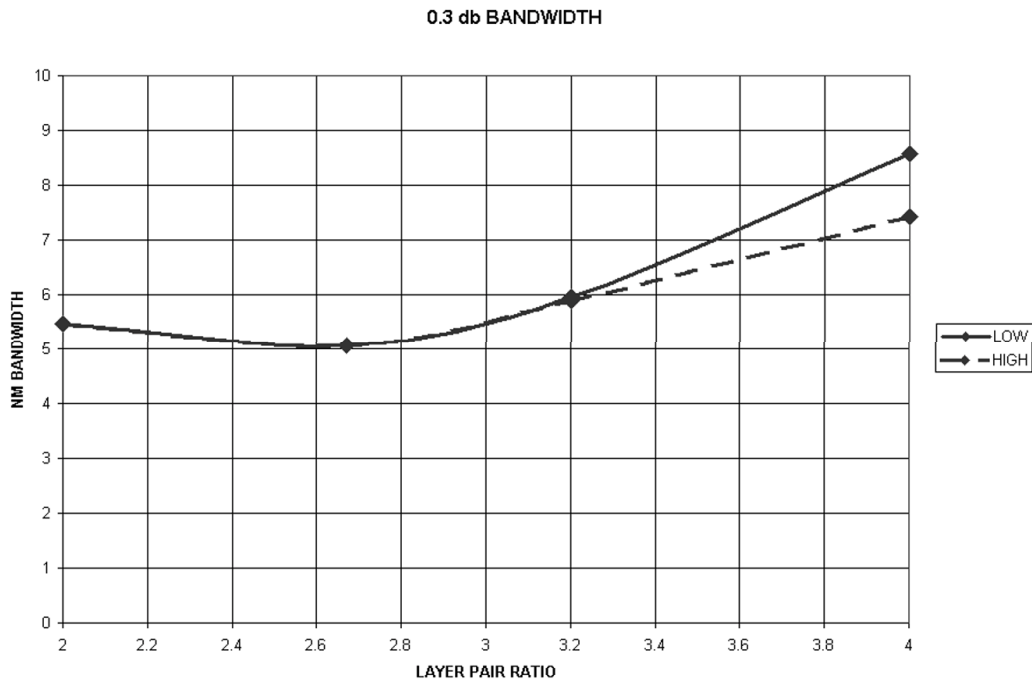


Fig. 12. Width of the top of the passband at 0.3 db versus the layer pair ratio.

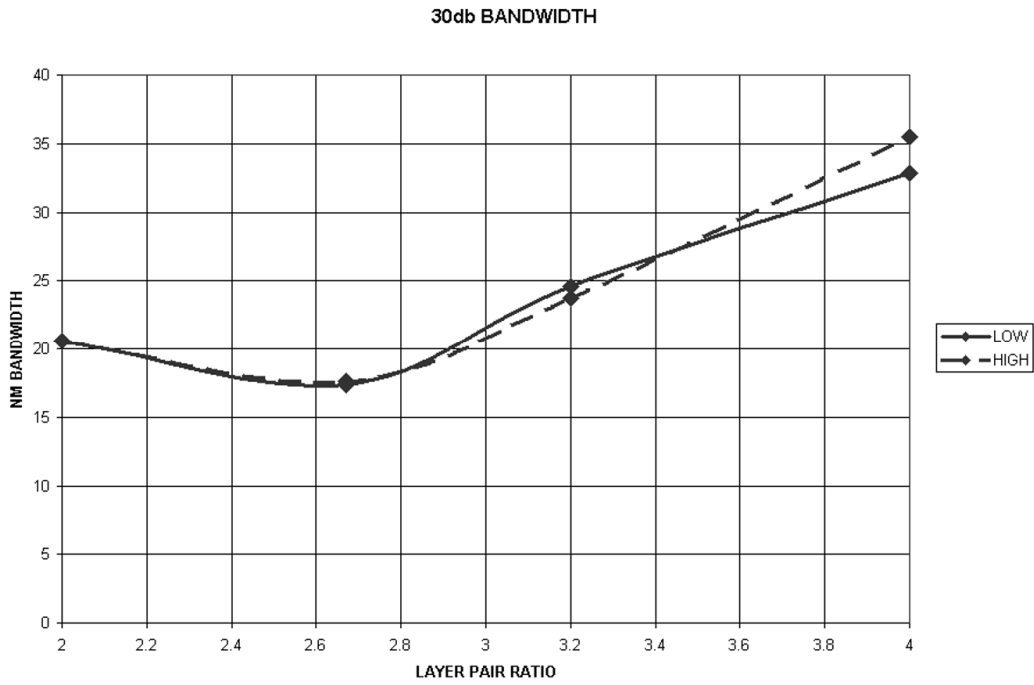


Fig. 13. Width of the skirt of the passband at 30 db versus the layer pair ratio.

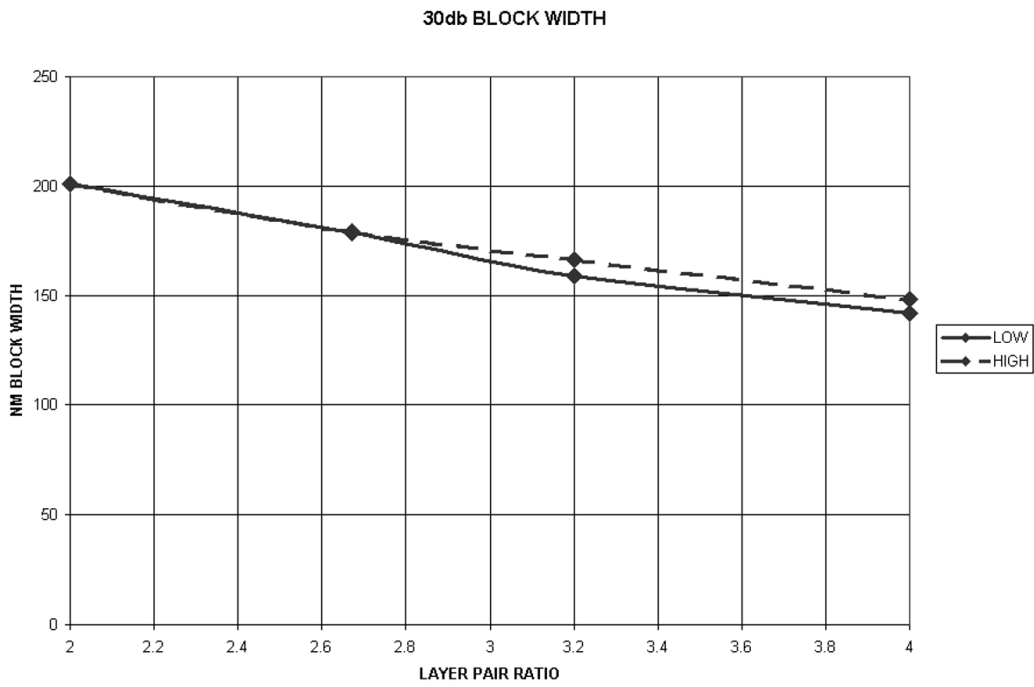


Fig. 14. Width of the blocked band at 30 db versus the layer pair ratio.

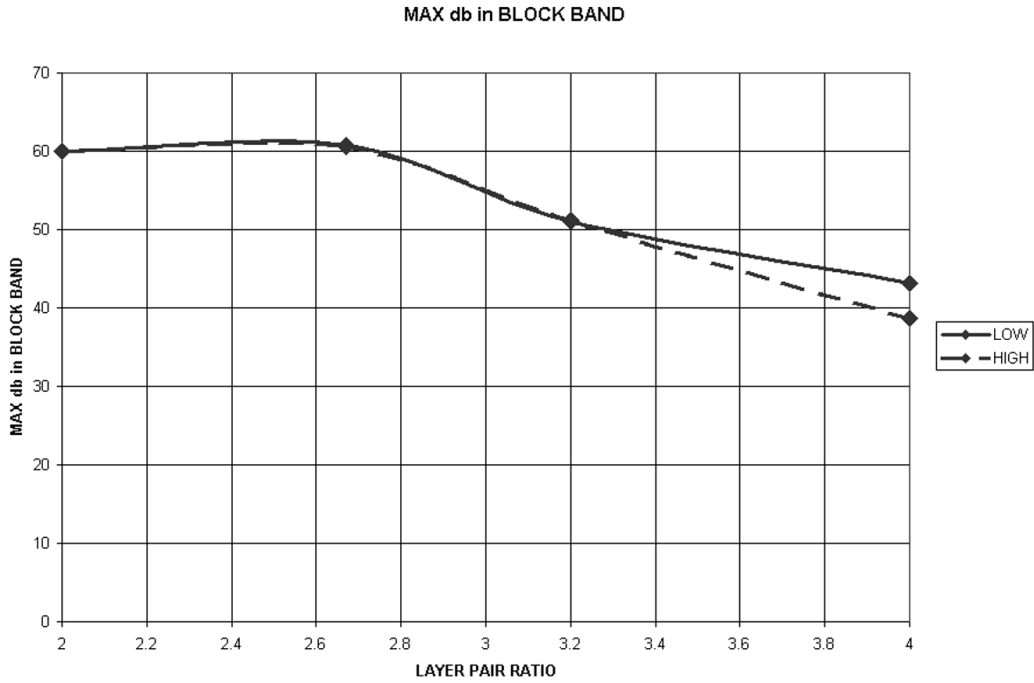


Fig. 15. Peak db transmittance in the block band versus the layer pair ratio.

WIDE LOW LAYERS, % M/M CUTS

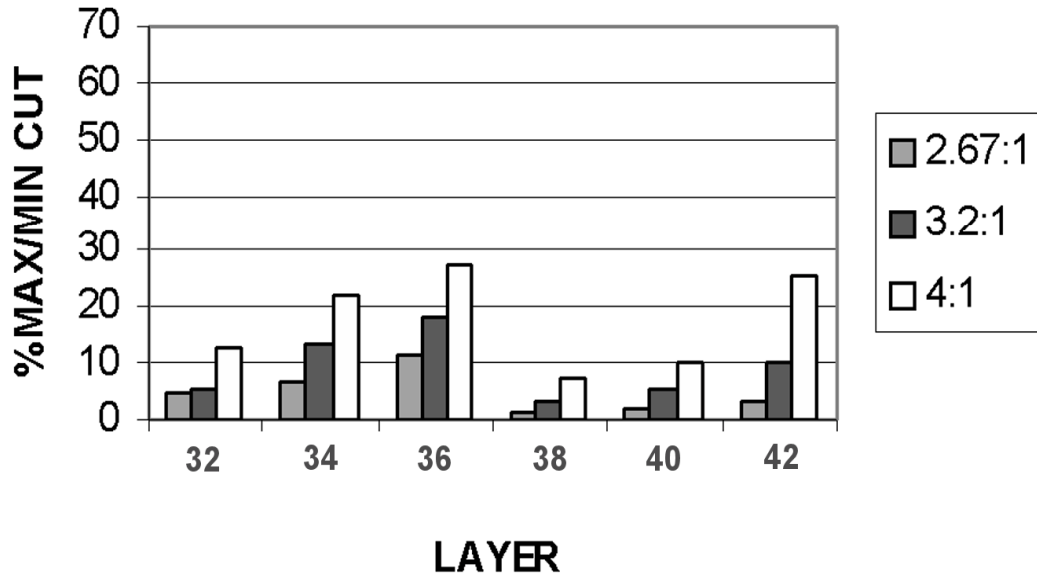


Fig. 16. Termination points of each two-turning-point layer in the third cavity of wide low index layer designs.

Figure 15 shows the peak db of transmittance in the block band as a function of layer pair ratio. At a ratio of 2:1, the peak db tends to be the same on both sides of the passband, but the peaks become unequal with increasing ratio, as seen in Fig. 9. The lesser peak has been plotted here rather than the more dense peak.

The critical factor in the subject of this section is to get the cut points far enough from the turning points to have a good change in transmittance with thickness for accurate and precise layer terminations, but to not degrade the key properties (bandwidth and blocking) of the NBP filter too much. The degrees of degradation have been shown above. The distance from the turning points in %Max/Min is shown in Figs. 16 and 17. The case of wide low layers at each of the two-turning-point layers in the last cavity is seen in Fig. 16. The first two cavities have very similar results. The wide high layer cases show even greater %Max/Min as seen in Fig. 17, but perhaps not so much as to dictate the decision between using wide low or wide high layers in the designs.

For any particular layer number, the results (with some allowance for small errors in processing) point to the fact that the %Max/Min is proportional to the layer pair ratio. This should make it easy to adjust the ratio to get the %Max/Min desired while keeping the effects on bandwidths and density under control.

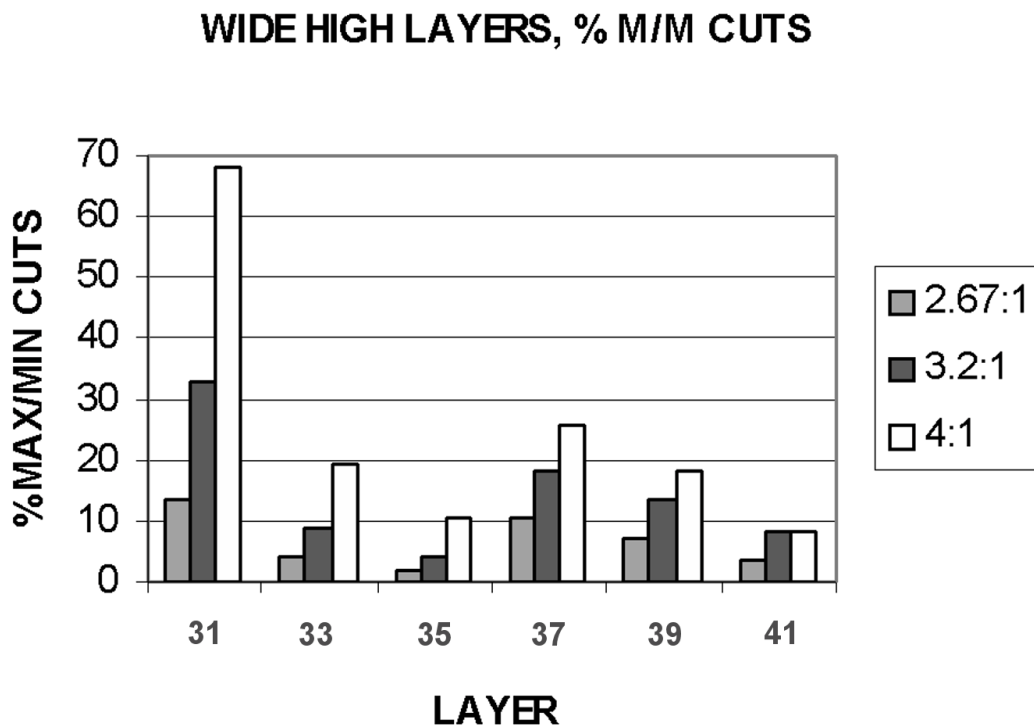


Fig. 17. Termination points of each two-turning-point layer in the third cavity of wide high index layer designs.

There is another empirically derived tool that should be helpful in this design process. For this case of a 5 nm bandwidth, three cavity NBP filter with these materials, the optical thicknesses of the spacer/cavity layer and the coupler layers can be calculated. The coefficients of the equations would probably need to be adjusted for other designs. For Eqns. 1 and 2, **TH** is the thickness of the high index layers in QWOTs of the passband wavelength and **TL** is the thickness of the low index layers. The calculation of cavity and coupler thicknesses using these equations should give

$$\text{Cavity Thickness} = 3.2765 + 0.7235 * TH \tag{1}$$

$$\text{Coupler Thickness} = 0.3872 + 0.6132 * TL \tag{2}$$

good centering of the band about the design wavelength once the appropriate AR layers have been designed (2 before and 3 after the stack). However, if a small adjustment is needed to center the band, the thickness of the coupler layers should be adjusted in tandem.

4. CONCLUSIONS

A new design approach for monitoring NBP filters has been described which gives the potential for less fabrication/production error to be gained by layer terminations at non-turning points while maintaining the benefits of error compensation at the monitoring wavelength. The monitoring of this new approach to NBP filter design offers the potential for error compensation and reduced layer termination errors due to layers being terminated at levels removed from the insensitive turning points. A key feature is that there tend to be two or more extrema within the monitoring of each pair, and this has a self calibrating effect for each layer pair.

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