ELSEVIER

Thin Solid Films 398–399 (2001) 1–9

thin solid films

www.elsevier.com/locate/tsf

Achieving narrow bandpass filters which meet the requirements for DWDM

R.R. Willey*

Willey Optical Consultants, 13039 Cedar Street, Charlevoix, MI 49720, USA

Abstract

Some of the most difficult optical coating requirements at this time are for narrow bandpass filters to be used in dense wavelength division multiplexing (DWDM). The design of these filters is relatively straightforward, but aids are given for estimating the design details needed to achieve specific bandwidth requirements. The compromises in the choice of materials for the filters are mentioned. In the control or monitoring during the production of such designs, the classical techniques benefit tremendously by self compensation effects of errors in spite of the hypersensitivity of the results to small individual uncompensated errors. The effects of errors and drifts in the control system are shown. A monitoring strategy and algorithm are suggested to maximize performance utilizing more of the available information and computing power. DWDM filter production contains extreme contrasts between the error forgiveness in some areas and requirements for rigid adherence to stable control in others.

Keywords: Narrow band pass filters; DWDM; Bandwidth

1. Introduction

At this time, DWDM filters are a topic of great interest in the fiber optics communications field. Very narrow bandpass filters are required to separate the many wavelengths which are traveling through a single fiber. The design of these filters is relatively straightforward, but the control or monitoring during the production of such designs is the most significant issue. We have given [1] aids for estimating the design details needed to achieve specific bandwidth requirements. It is shown that DWDM filter production contains extreme contrasts between the inherent error compensation in some areas and requirements for rigid adherence to stable control in others.

Fig. 1 shows a real design for a 1550-nm passband filter using SiO_2 and Ta_2O_5 for the low and high index materials. The figure also shows typical specification limits for a 100-GHz filter wherein the adjacent channels must have greater than 20 dB blocking of one channel to the others on 0.8 nm (100 GHz) spacing, and each must have better than 0.3 dB transmittance in a 0.34-nm (42.5 GHz) pass band.

The last two layers are an antireflection (AR) coating for the layer stack in air. The AR coatings may vary from design to design, but are all essentially a 'V-coat' providing an impedance match between the final cavity mirror stack and the medium (air or vacuum). More than two AR layers have been found to be of no advantage in the case of these narrow bandpass filters. Note that, if the back side of a thin substrate is not coated with a proper AR, there can be ripples in the passband as illustrated in Fig. 2. These depend on the substrate thickness and constitute an interference between the two surfaces of the substrate.

2. Estimation for designs

It is practical to estimate the pass band width (BW) and blocking band width of a DWDM filter before designing the filter as a function of refractive indices, spacers, number of layer pairs, and number of cavities. This can be a guide as to which design parameters could

---

* Tel.: +1-231-237-9392; fax: +1-231-237-9394.
E-mail address: rwilley@freeway.net (R.R. Willey).

0040-6090/01/$ - see front matter
PII: S0040-6090(01)01295-0

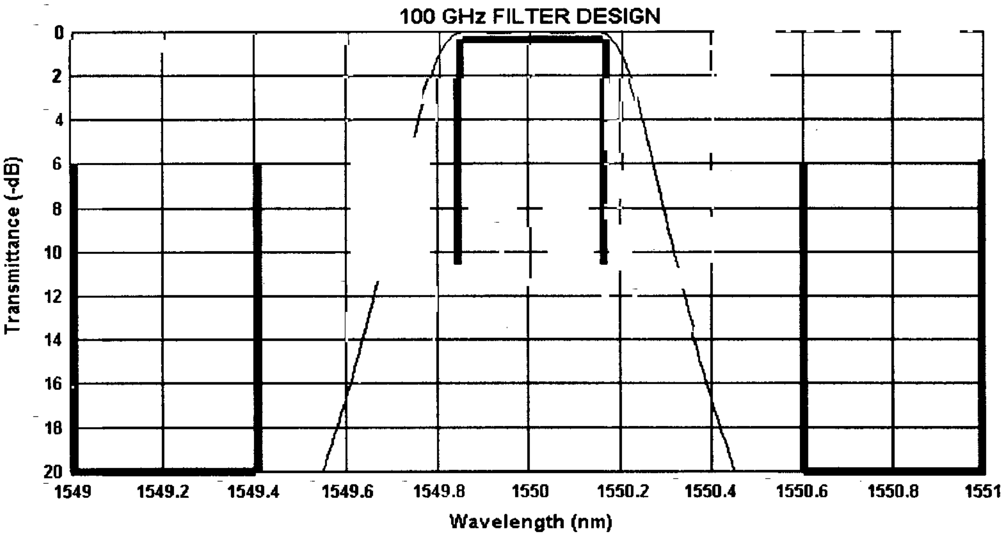

Fig. 1. Three (3) cavity NBP filter for 100 GHz DWDM applications. The design at 1500 nm is: (1H 1L)9 4H (1L 1H)9 1L (1H 1L)9 4H (1L 1H)9 1L (1H 1L)9 4H (1L 1H)8 1L.52072H.86628L. Specification limits are also shown.

be used to gain a desired result. We have described [1] the derivation and resulting formulas for these estimates. The extremes of the sampling ranges were:

#Layer-Pairs	5 to 13
#Spacer-HW's	1 to 5
Index-Difference	0.31 to.87
Average-Index	1.615 to 1.895

Fig. 3 shows that the BW is a strong function of the difference of index and of the number of layer pairs. Fig. 4 shows that both the average index and the number of half waves in the spacer layers do not have a strong effect on the BW. It is therefore advisable to obtain the gross features of the design (rough BW and blocking) by the number of layer pairs in the mirror stacks and the index difference. The materials which determine the index difference are usually fixed by the needs for wavelength stability with temperature. The average index is also usually fixed by these same considerations. The fine details of the BW can then be adjusted with the number of half waves in the spacers. Table 1 gives equations and coefficients from which the BW can be predicted for three cavity filters by knowing the four parameters discussed.

At this time, many new coating systems being applied to the production of DWDM filters are using dual ion beam sputtering (DIBS) to deposit Ta_2O_5, reactively, from titanium metal targets. The low index material is SiO_2 also deposited by DIBS from fused silica targets. Takashashi [2] described how the coefficient of thermal expansion of the substrate is critical to the temperature stability of the center wavelength of narrow bandpass filters and the stress relationships that exist. Zöller et al. [3] also reported on temperature stabilization, and Faber et al. [4] touched on this substrate choice and other aspects of DWDM filter design and production. If a different high index material were used, a different substrate material might be required to minimize temperature sensitivity.

3. Deposition monitoring

The three cavity DWDM filter design shown in Fig. 1 would have 114 layers and an ideal optical monitor trace as shown in Fig. 5. The most critical monitoring area near the first spacer layer (number 19) is seen on an expanded scale in Fig. 6. It can be seen that the monitor signal level has decreased two orders of magnitude from the starting layer to the spacer layer.

If the noise in the monitor signal were 1% peak-to-peak (p–p), the monitoring curve for the first layer might look like Fig. 7. Note, however, that this noisy monitor curve was terminated at 5% beyond the actual quarter wave optical thickness (QWOT) desired, but it would be very difficult for an operator to have sensed that overshoot. If one were to have this signal to noise ratio (SNR = 100 at the start) and reach the layers approximately 12 to 22, the noise would be as large as the signal and probably impossible for an operator to decide when to terminate a layer. If we were to improve the SNR by two orders of magnitude (SNR = 10 000), the monitor signal at layer 20 might look like Fig. 8 which also illustrates a 5% overshoot. The situation is the worst at layer 20, where it would be difficult to decide from observation whether the termination was a 0% or 5% overshoot. The operator might be expected to terminate a layer with less overshoot than that, perhaps 2% at best. Therefore, the effective SNR must be quite high in order to expect layer terminations

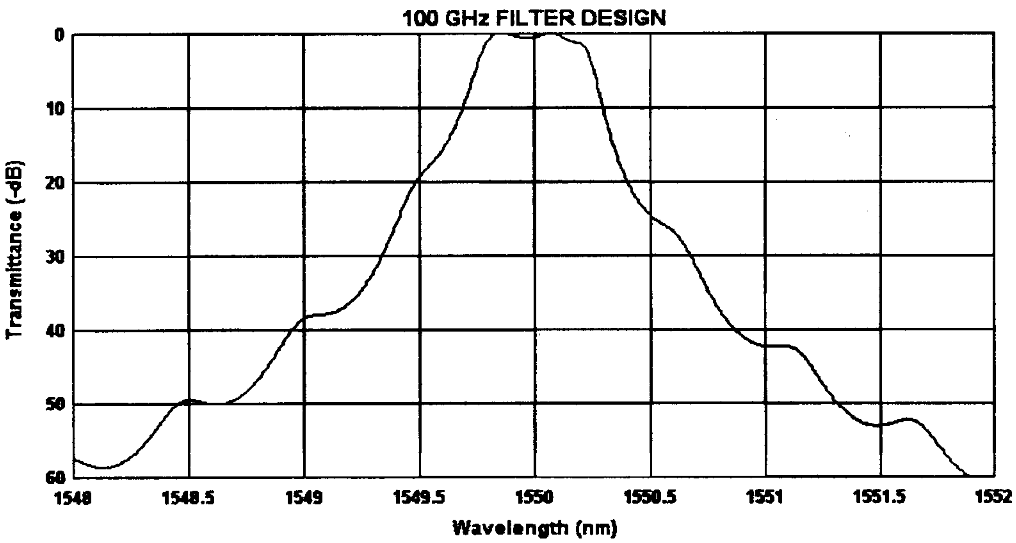

Fig. 2. Ripples due to interference of the front and back side reflections of a thin substrate which is not coated with a proper AR on the back side.

within even a few percent of the desired QWOT turning points.

4. Effects of errors

The sensitivity of the performance of this filter to random thickness errors in the layers is striking. Fig. 9 shows that 0.01% random errors will totally destroy the yield of useful filters requiring <0.3 dB losses for DWDM applications. This is mostly due to the in-band losses and not particularly due to the position of the rejected wavelengths. Errors of 0.002% have been found to be generally satisfactory. Even 0.01% layer termination accuracies are not possible with current technology. Therefore, it would be impossible to produce such filters if it were not for the beneficial effects of error compensation.

With reference to Fig. 6, the 16th layer might be terminated in error at A′ Instead of at A. The 17th layer would still be terminated as close to the turning point B as possible. This means that the second layer would be thicker than the design by just enough to make up for the error in the first layer and produce two full QWOTs for the pair of layers. Similarly, if the 17th layer terminated too late at B′ instead of B, the 18th layer would just make up for the loss if terminated at the turning point. Bousquet, et al. [5] discuss this type of compensation in some detail. This can make an enormous difference in the performance since the mean phase of the interfaces of the layers will remain centered on the ideal design relationship.

One major criterion in the quality of a DWDM filter is the dB loss in the transmission (T) passband. The ripple is also specified, but we will here consider only the average transmission (T_{ave}) loss in the passband. We have applied [1] a 2% of a QWOT error to each layer in turn and computed T_{ave} with this error. It was clear that the effects are by far the greatest for the layers nearest the spacer (or cavity) layers. This severe effect could be seen to cause losses as great as 24 dB at the central spacer. However, such extreme situations are not expected in a real case where each subsequent layer termination would be attempting to stop at the next turning point and thereby compensate the foregoing errors. We also reported [1] a scheme to calculate the change in reflection with the change in thickness of a layer at the turning points. The effect of errors on the T_{ave} as a function of layer position was estimated by the product of these two results. This result is plotted in Fig. 10 and shows how critical the layers near the spacers can be. The coupling layer effects are almost invisible on this scale. This coupler insensitivity to errors was somewhat a surprise. The optical signal for coupler layer termination has very little transmittance change and is well known for being unreliable and difficult to determine. Its termination by crystal thickness or time at a constant rate seems to be the most practical solution. However, it is otherwise at the most insensitive position in the design. Terminations of layers subsequent to the coupler at their turning points will tend to compensate errors in the coupler layer.

5. Error compensation

When the 2% errors were used to generate the results above, the thickness of the layer following the layer with the error was also reoptimized for the best T_{ave}. In every case, the T_{ave} was restored to the ideal value and that layer was terminated at the turning point. This showed that even an error at the most sensitive layer

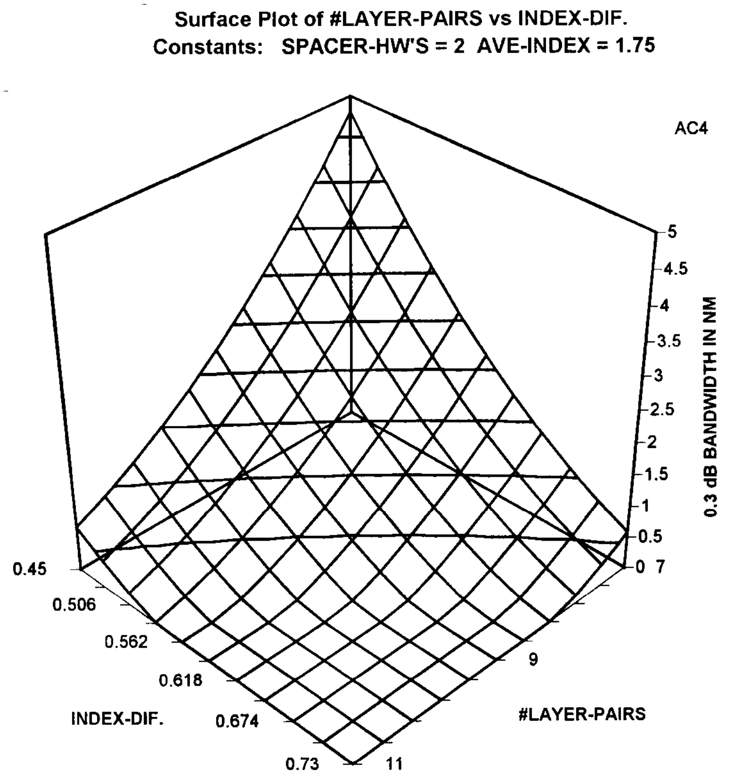

Fig. 3. Shows that the BW is a strong function of the difference of index and of the number of layer pairs.

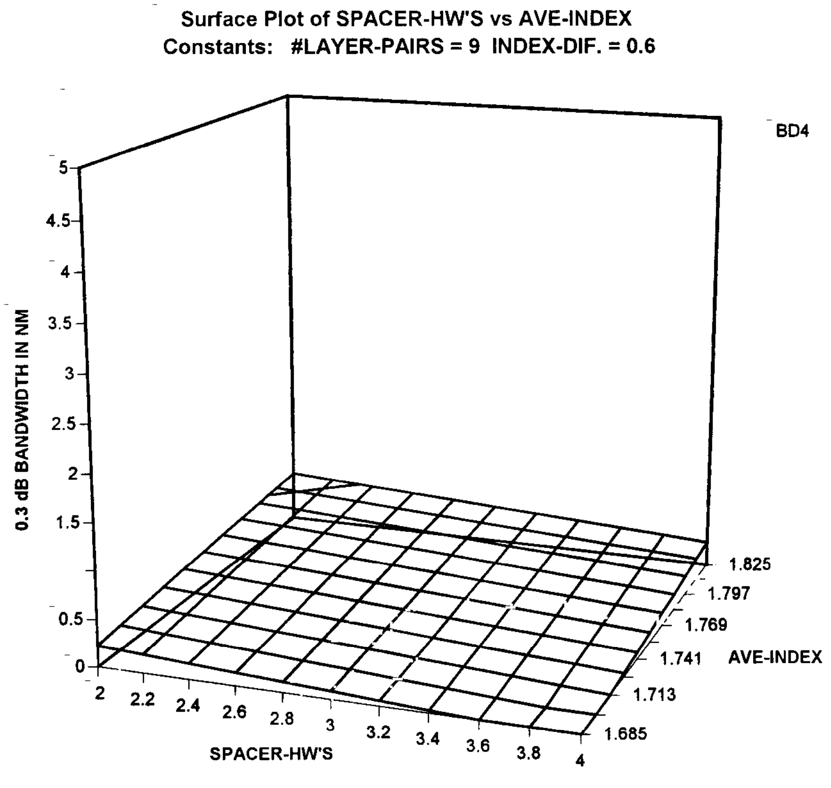

Fig. 4. Shows that both the average index and the number of half waves in the spacer layers do not have a strong effect on the BW.

Table 1
Equations and coefficients from which the bandwidth (BW) can be predicted for three cavity filters by knowing the high and low indices number of layer pairs per mirror, and the number of half waves in the spacer layers

T_{AVE} IN dB =

Const
+ A * #LAYER-PAIRS
+ B * #SPACER-HALF-WAVES
+ C * INDEX-DIFFERENCE
+ D * AVERAGE-INDEX
+ AC * #LAYER-PAIRS * INDEX-DIFFERENCE
+ AA * #LAYER-PAIRS ^2
+ CC * INDEX-DIFFERENCE ^ 2

	0.3dB	20dB
Const	40.42101	99.05472
A	−4.43899	−11.1974
B	−0.1527	−0.39881
C	-65.9173	−150.719
D	2.477614	5.069167
AC	2.696339	6.397634
AA	0.12923	0.339522
CC	28.63107	63.3527

can be almost totally corrected for at the next turning point. We have performed other simulations where the error was not corrected until a layer later than the next. It was generally found that the error could be reasonably well compensated in a later layer, but the more the number of intervening layers before the correction, the greater was the loss generated in T_{ave}. This seems to be consistent with the concept that the intervening erroneous layer interface positions each contribute reflections to the T_{ave} losses because they have phase errors. The more there are of such contributions, the more will be the losses in T_{ave}.

Even though compensation for errors is always at work, there are still real residual errors in each layer which will make some contribution to the reduction of T_{ave}. If those errors were uncompensated, we would have the situation seen in Fig. 9. A realistic modeling of errors with compensation as it actually happens in common practice has not been reported to our knowledge, and we are presently working to develop such a model.

6. Drift in monitoring wavelength

At least one of the popular coating systems used for DWDM filter fabrication today uses a laser such as

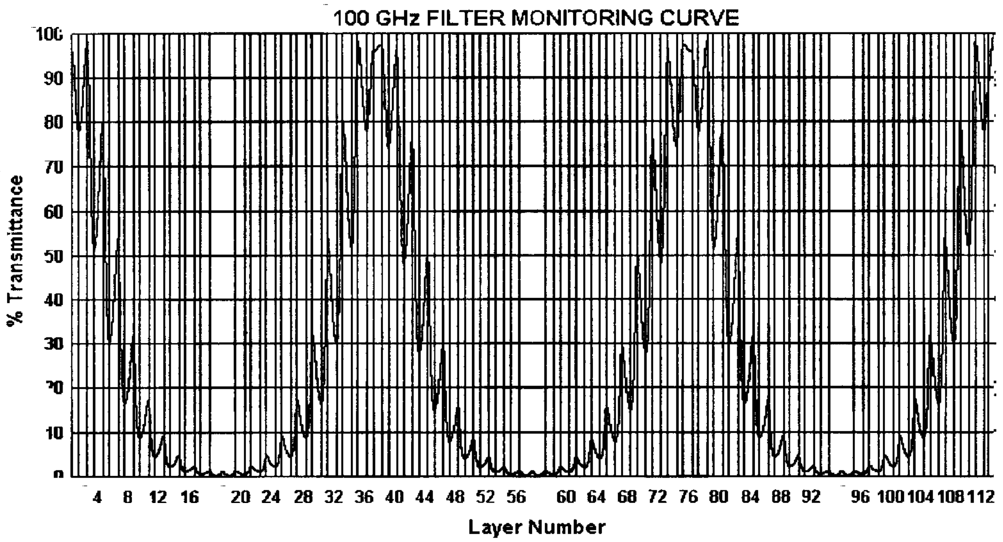

Fig. 5. Ideal monitor trace of the three-cavity DWDM filter design shown in Fig. 1

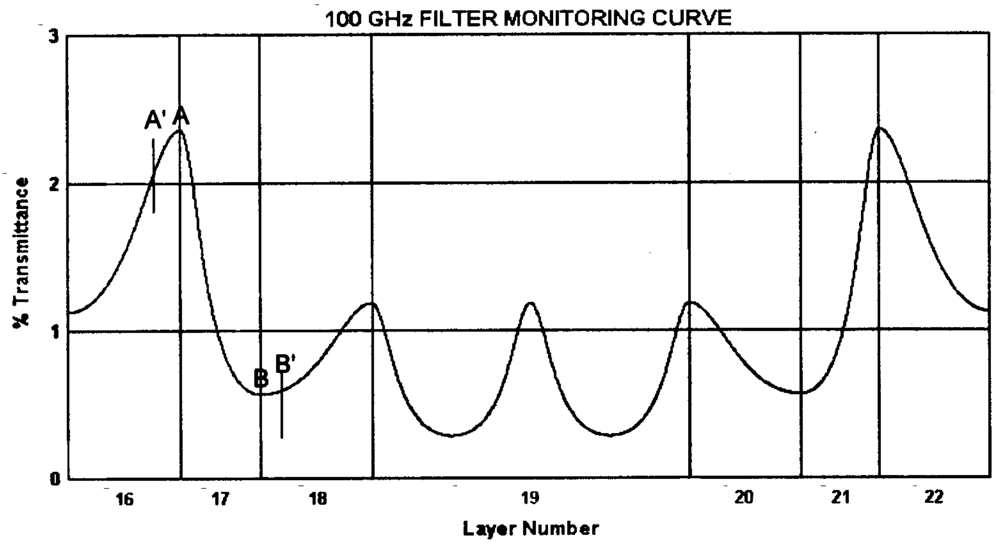

Fig. 6. Most critical monitoring area near the spacer layer (number 19) as seen on an expanded scale from Fig. 5

might be used in the final communications application of the filters as the optical monitoring source. The stability of the monitoring wavelength over the whole deposition time of the filter is critical. If the wavelength of the monitor drifts during the deposition, the layer thicknesses will drift with it, even though the compensation effects for errors will still be operative. We have simulated linear drifts of 0.1, 0.2 and 0.3 nm over the time of the monitoring. The results are shown in Fig. 11 in comparison with the ideal filter (0.0 nm). The filter is nominally 0.4 nm wide at 1.0 dB, and it can be seen that any drift as large as approximately 0.1 nm will cause problems with the usual specifications of < 0.3 dB ripple and losses. The implication is that the drift of the monitor wavelength should be almost an order of magnitude less than the filter bandwidth.

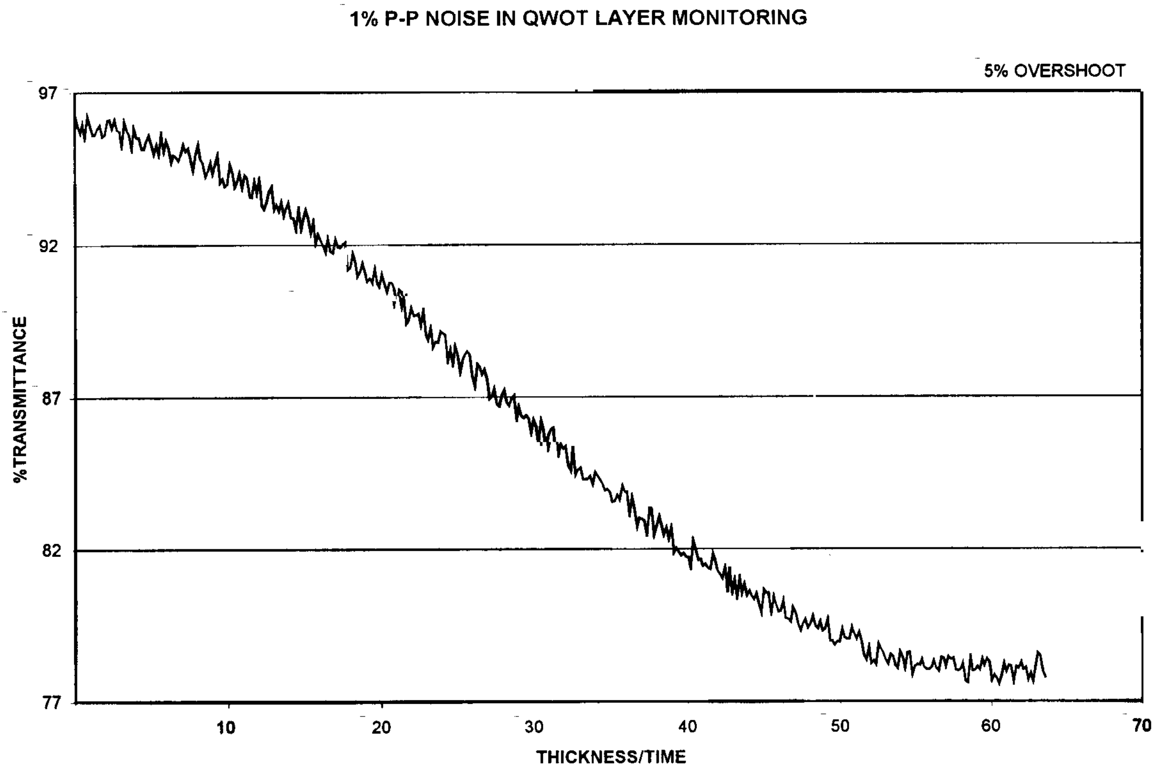

Fig. 7. Monitoring curve for the first layer from Fig. 5 if the noise in the monitor signal were 1% peak-to-peak.

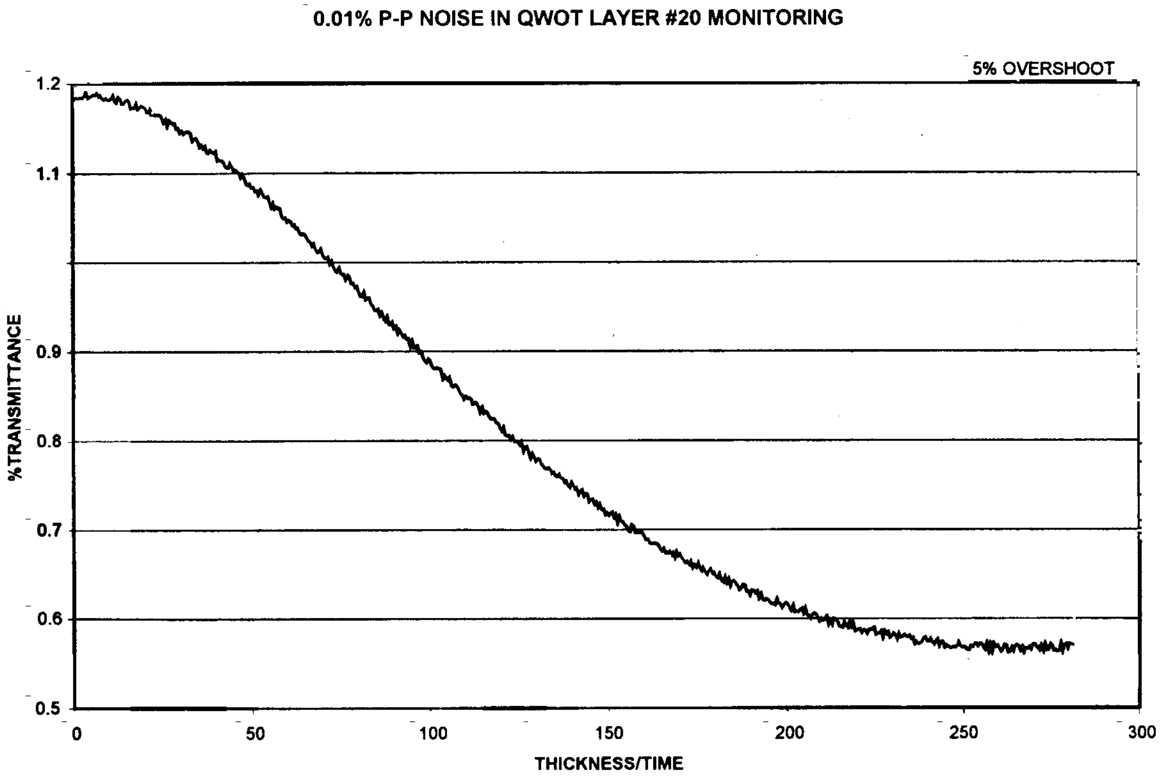

Fig. 8. Monitoring curve for layer 20 from Fig. 6 if the noise in the monitor signal were 0.01% peak-to-peak.

7. Monitoring passband width

There are also potential problems if the bandwidth of the monitor wavelength is too wide for the application. The wavelengths on either side of the band center produce monitoring modulations that become more and more out of phase with each other with increasing coating thickness and cause the overall detector signal to reduce in modulation. We have simulated the effects of various bandwidths on the monitoring signal using a diffraction limited slit image as the model. Fig. 12 shows the monitor trace for layers 94–114 of the filter discussed above with monitor bandwidths of 0.025 (very narrow), 0.1, 0.3 and 0.4 nm. The start of the loss in signal modulation can particularly be seen for 0.4 nm. The effect of this on final filter performance would

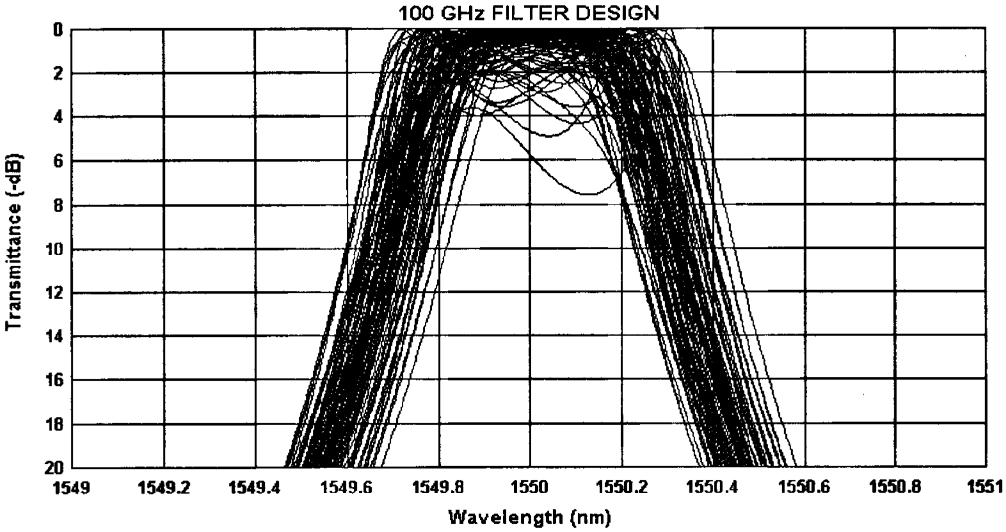

Fig. 9. Effects of 0.01% random errors is seen to totally destroy the yield of useful filters requiring <0.3 dB losses for DWDM applications.

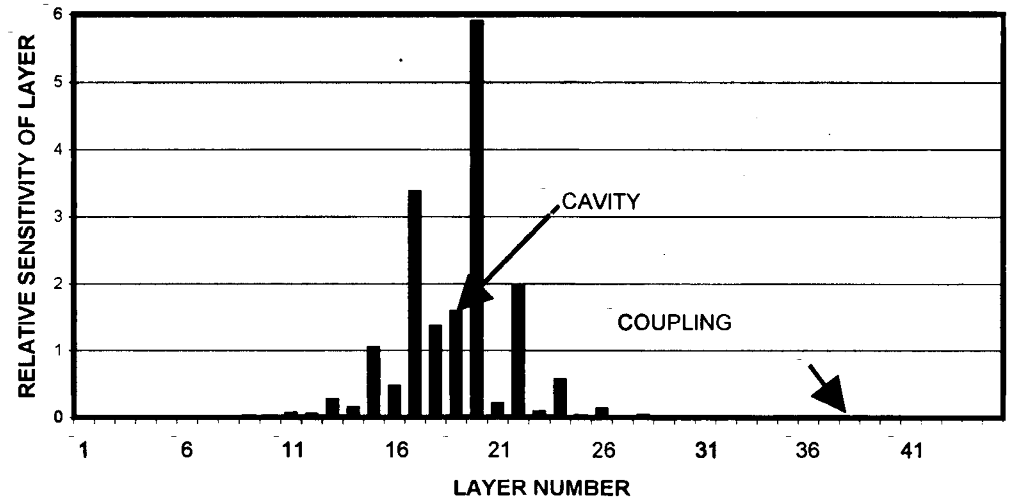

Fig. 10. Relative overall sensitivity of each layer to thickness errors for the first third of the filter of Fig. 1

depend on whether it lead to terminating layers too soon or too late with respect to the desired QWOT turning points. We found this result somewhat surprising in that it does not appear that a monitor bandwidth almost as wide as the bandwidth of the filter being made would cause significant error. This points to the fact that monitoring with a laser may not be absolutely necessary if an adequately narrow and stable monochromator is available.

8. Suggestions for computer aided monitoring

Schroedter [6] described a monitoring system which combines the best features of the optical monitor with the crystal monitor to give greater accuracy than is available from either monitor by itself. A crystal monitor needs to be calibrated to a known optical thickness by spectrophotometer readings of the results of test runs. Schroedter did this in real time rather than after a test run by a computer automated procedure with a system that had both a crystal monitor and an optical monitor. The photometric level was sampled and stored in the computer at equal intervals of crystal thickness readings. Variations in the deposition rate have little direct effect because the sampling was vs. crystal thickness, not time. As a sufficient number of points are gathered, it becomes possible to fit the data for the layer to the anticipated monitoring curve and predict where the turning point at the optical monitor wavelength will occur. The key factors here are that the crystal is precise but not accurate, and the optical monitor is accurate in optical thickness, but not precise.

It appears that some attempts have been made to incorporate turning point prediction into DWDM fabri-

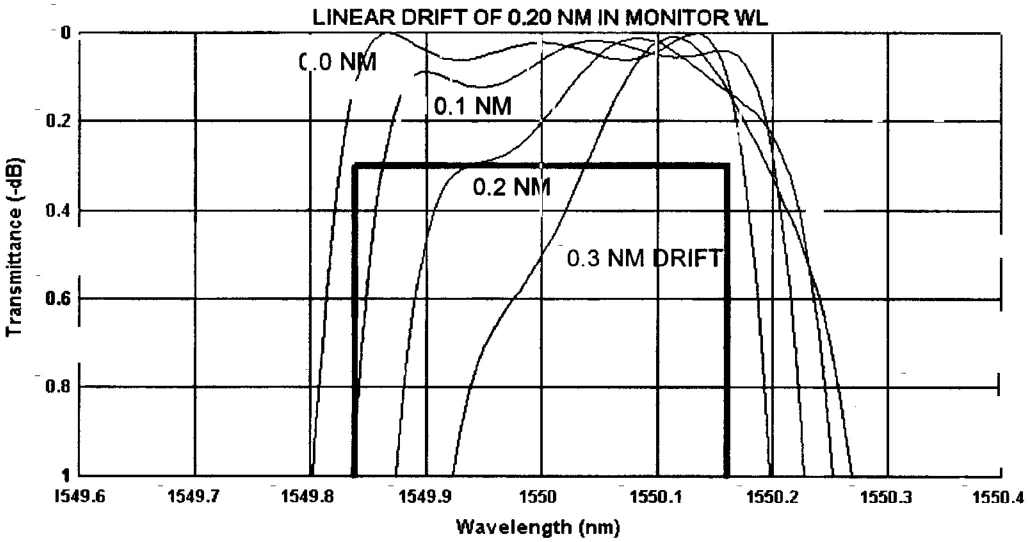

Fig. 11. Errors due to linear drifts in the monitoring wavelength of 0.0, 0.1, 0.2 and 0.3 nm over the total time of the monitoring.

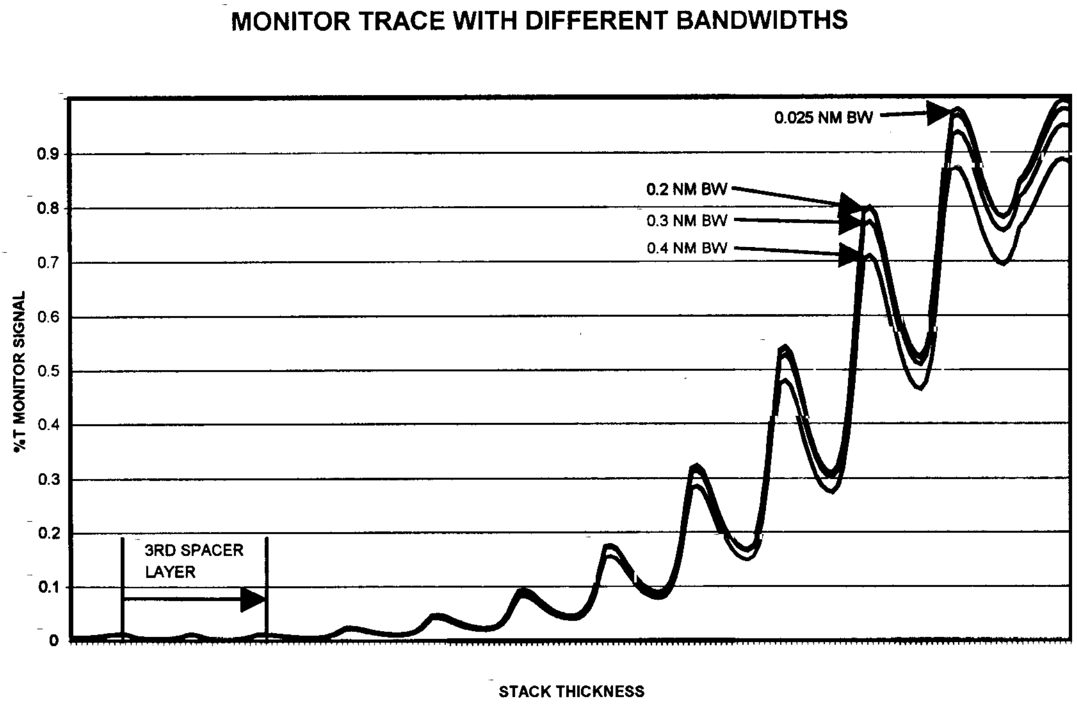

Fig. 12. Monitor traces for layers 94 through 114 with monitor wavelength bandwidths of 0.025, 0.1, 0.3 and 0.4 nm.

cation, but we are not privy to whether they have the sophistication of the Schroedter [6] technique. The equipment which we have observed firsthand did not, since it had no crystal monitor, it presumed a constant deposition rate. It is also advantageous to have a crystal monitor for rate control and for dealing with coupler layers and, in some cases, the first of the last two AR layers. The data from this could then be used in a Schroedter-like technique.

For best results, it is necessary to predict the expected monitoring curve shape of the layer being deposited. In order to do this, the index of the layer and the reflectance at its start are needed. If both of these were known exactly, the locus of the layer on a reflectance circle diagram (and thereby transmittance) could be exactly predicted. The actual signal with its inherent noise could be continually fit to the predicted curve derived from this. At the point of best fit to the desired termination, the layer deposition would be stopped. Since there are errors in the knowledge of the index and reflectance at the layer starting point, the software needs enough sophistication to handle this. It should also be able to handle the fact that the layer may have started before or after the previously intended turning point. The software also needs the ability as implied by Schroedter to predict a turning point enough in advance of its actual occurrence to terminate the layer at 'exactly' that turning point. Another technique of possible value, depending on the stability of photometric level of the laser and detector system with time, would be to monitor the level of the light into the monitor and divide the output by that level. This is in case there is any drift in that light level with time, and would be a first approximation of a true double beam spectrophotometer.

9. Conclusions

We have provided aids for estimating the design details needed to meet specific DWDM bandwidth requirements. The hypersensitivity of the filters to small individual uncompensated errors, which layers are most sensitive to errors, and the self compensation effects on errors have been discussed. The effects of monitoring wavelength drift and bandwidth on the control system are shown. A monitoring strategy is suggested to maximize performance utilizing more of the available information and computing power.

References

[1] R.R. Willey, Proc. Soc. Vac. Coaters 44 (2001) 0–2.
[2] H. Takashashi, Appl. Opt. 34 (1995) 667–675.
[3] A. Zöller, R. Glötzelmann, K. Matl, D. Cushing, Appl. Opt. 35 (1996) 5609–5612.
[4] R. Faber, K. Zhang, A. Zoeller, SPIE 4094 (2000) 58–64.
[5] P. Bousquet, A. Fornier, R. Kowalczyk, E. Pelletier, P. Roche, Thin Solid Films 13 (1972) 285–290.
[6] C. Schroedter, SPIE 652 (1986) 15–20.