Estimating the Properties of DWDM Filters Before Designing and Their Error Sensitivity and Compensation Effects in Production

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ABSTRACT

It is practical to estimate the pass band width (BW) and blocking band width of a dense wavelength division multiplexing (DWDM) filter as a function of refractive indices, spacers, number of layer pairs, and number of cavities before designing the filter. This can be a practical design guide as to which parameters should be used to gain a desired result. The derivation and resulting formulas for these estimates are described and presented. The successful production of a final design then depends on the process stability, monitoring techniques, and related errors. The amazing error compensation capability of optical monitoring at the pass band wavelength is the major factor that makes the production of DWDM filters at all possible. The resulting performance is much more sensitive to errors in some layers of a design than others. We show errors that are redeemable and how that is accomplished.

INTRODUCTION

DWDM is a topic of great interest in the fiber optics communications field. Very narrow bandpass filters are required to separate out the many wavelengths which are traveling in a single fiber. This seems to one of the most challenging optical coating production problems of this period. The design of these filters is relatively straightforward, but we will give aids for estimating the design details needed to achieve specific bandwidth requirements. The control or monitoring during the production of such designs is the most significant issue and some aspects of that will be discussed here. It will be seen that DWDM filter production contains extreme contrasts between the error forgiveness in some areas and requirements for rigid adherence to stable control in others.

ESTIMATING DWDM FILTER PROPERTIES

It is practical to estimate the pass band width and blocking band width of a DWDM filter as a function of refractive indices, spacers, number of layer pairs, and number of cavities before designing the filter. This can be a practical design guide as to which parameters should be used to gain a desired result. We will describe the derivation and resulting formulas for these estimates. The successful production of a final design then depends on the process stability, monitoring techniques, and related errors.

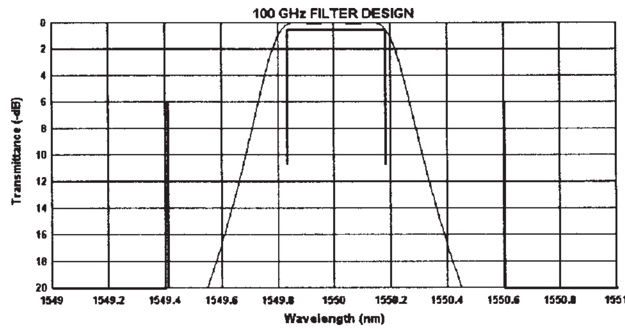

Figure 1: Three-cavity NBP filter for 100 GHz DWDM applications. The design is (1H 1L)9 4H (1L 1H)9 1L (1H 1L)9 4H (1L 1H)9 1L (1H 1L)9 4H (1L 1H)8 1L .52072H .86628L

Observing that the three-cavity filter seen in Figure 1 is generally well suited to the typical 100 Ghz requirements, we performed a systematic investigation over the likely parameter space using design of experiments methodology [1] (DOE). Four variables were considered: indices of the high and low index materials, the number of layer pairs in each mirror, and the number of half waves in the spacer layers. However, the indices were combined to form what was deemed to be two more meaningful variables: the difference in index (n_H-n_L), and the average index ((n_H+n_L)/2). The extremes of the sampling ranges in a Box-Wilson or central composite design [1] (CCD) configured DOE were:

# Layer-Pairs	5 to 13
# Spacer-HW's	1 to 5
Index-Difference	.31 to .87
Average-Index	1.615 to 1.895

The most likely cases are well within these ranges. Figure 2 shows the results of the regression analysis.

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Y-hat Model					
Factor	Name	Coeff	P(2 Tail)	Tol	Active
Const		0.22070	0.2011		
A	AYER-PAI	-1.04402	0.0000	1	X
B	ACER-H	-0.15270	0.1066	1	X
C	NDEX-DIF	-1.10118	0.0000	1	X
D	VE-INDE	0.17343	0.0698	1	X
AC		0.75498	0.0000	1	X
AA		0.51692	0.0000	0.920	X
CC		0.56117	0.0000	0.920	X

Rsq	0.9587
Adj Rsq	0.9417
Std Error	0.4390
F	56.4098
Sig F	0.0000

Source	SS	df	MS
egressio	76.1	7	10.9
Error	3.3	17	0.2
Total	79.4	24	

Figure 2: The results of the regression analysis of the data.

Figure 3 shows that the BW is a strong function of the difference in index from n_H to n_L, and of the number of layer pairs. Figure 4 shows that both the average index of n_H and n_L 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 index difference (which is usually fixed by other considerations) and the number of layer pairs in the mirrors. The fine details of the BW can then be adjusted with the number of half waves in the spacers. The average index is also usually fixed by other considerations. Therefore, the design is first set as close as possible to the required results with the number of layer pairs and then refined by the number of half waves in the spacers.

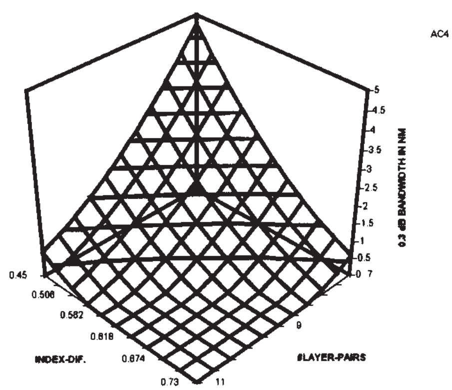

Figure 3: The BW is a strong function of the difference of index and of the number of layer pairs.

Table I, which was derived from the information in Figure 2, gives equations and coefficients from which the 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. This is easily entered into a spreadsheet program for routine calculations in the design process. It could also be useful to find the difference between n_H and n_L from and actual design run. Since the index of n_L is likely to be close to 1.45-1.46, the index n_H can be determined to the accuracy that n_L is known. This does however require that the results are good (have the right spectral shape) other than bandwidth differences due to the index being different from what was assumed. With this knowledge, the design can then be adjusted to give the desired results.

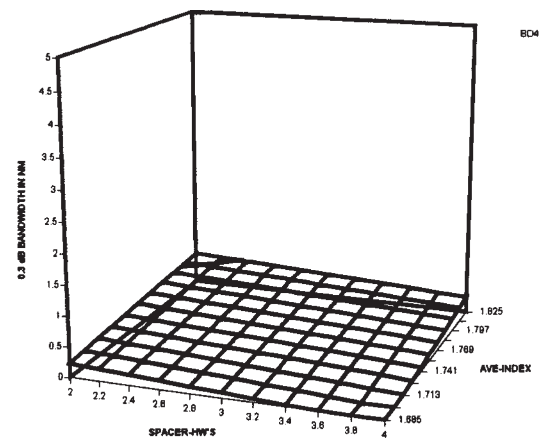

Figure 4: Shows that both the average index and the number of half waves in the spacer layers do not have a strong effect on the BW.

Table I: Equations and coefficients from which the BW can be predicted for three-cavity filters.

T-AVERAGE IN dB
= Const
+ A * # LAYER=PAIRS
+ B * # SPACER-HALF-WAVES
+ C * INDEX-DIFFERENCE
+ D * AVERAGE-INDEX
+ AC * # LAYER-PAIRS * INDEX-DIFF.
+ AA * # LAYER-PAIRS ^ 2
+ CC * index-difference ^ 2

	0.3 dB	20 dB
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

DWDM FILTER MONITORING

The three-cavity DWDM filter design shown in Figure 1 would have 114 layers and an ideal monitor trace of well known form. The first cavity has 37 layers and the most critical monitoring area near the spacer layer (number 19) is seen on an expanded scale in Figure 5. It can be seen that the monitor signal has dropped two orders of magnitude from the starting layer to the spacer layer.

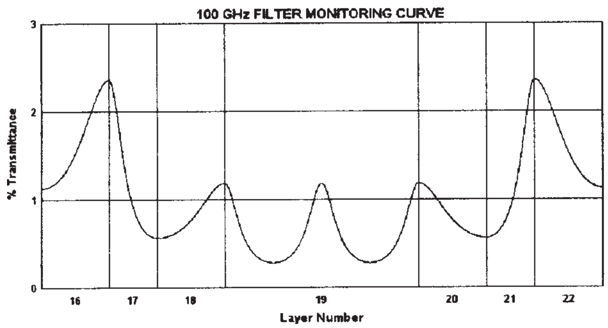

Figure 5: Monitor trace of layers near the first spacer (cavity) layer (19) of a 3-cavity DWDM filter.

If the noise in the monitor signal were 1% peak-to-peak (p-p), the monitoring curve for the first layer would look like Figure 6. Note, however, that this noisy monitor curve was terminated at 5% beyond the actual 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 around 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 would look like Figure 7, which illustrates what a 5% overshoot would look like in this case. The situation is known to be the worst at layer 20, where it would be difficult to decide from observation whether the trace was 0% or a 5% overshoot the “perfect” QWOT. Therefore, as we will discuss below, the effective SNR must be quite high in order to expect to terminate layers within even a few percent of the desired QWOT’s.

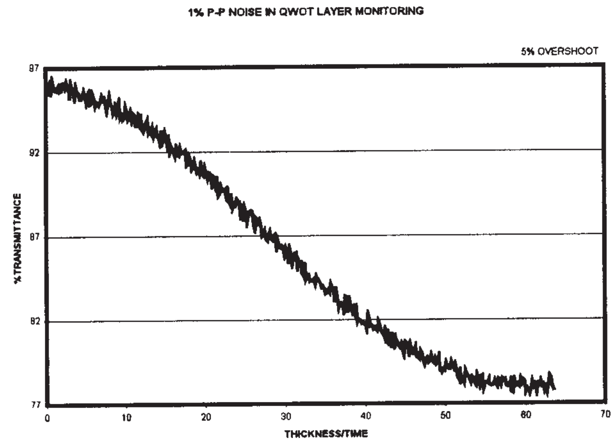

Figure 6: Monitor trace of first layer with 1% p-p noise and a 5% QWOT overshoot.

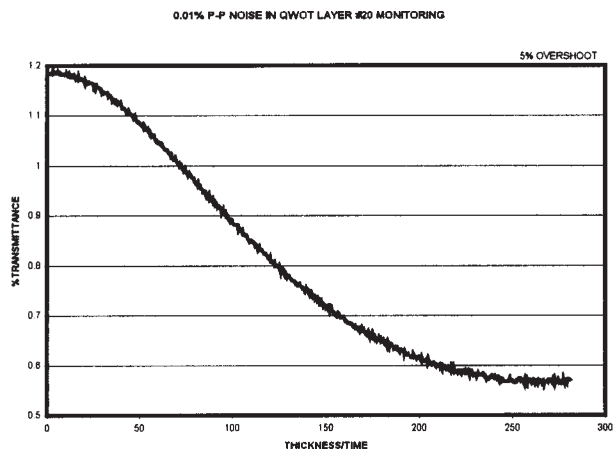

Figure 7: Monitor trace of 20th layer with 0.01% p-p noise and a 5% QWOT overshoot.

The sensitivity of this filter to random thickness errors in the layers is striking. Figure 8 shows that 0.01% random errors will totally destroy the yield of useful filters for typical DWDM applications, both in the in-band losses and the position of the rejected wavelengths. It has been found that random errors of 0.002% would generally be satisfactory. There are approximately three orders of magnitude between this and the 2% errors that an operator might be expected to achieve on the more critical terminations! How then can we ever expect to produce an acceptable filter? The answer is that the natural effects of error compensation may overcome these problems.

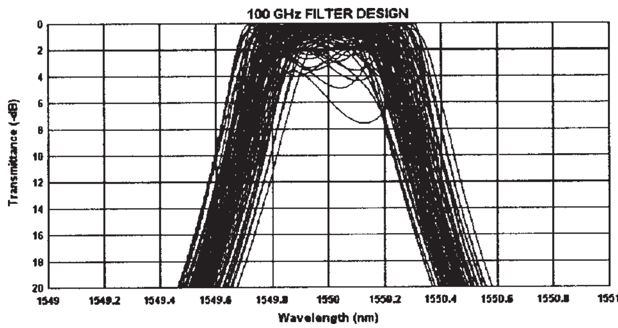

Figure 8: Effect of 0.01% random errors on filter shape.

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 concentrate here on the average transmission (T_{ave}) loss in the passband. We applied a 2% of a QWOT error to each layer in turn and computed the average T in the passband with this error.

Figure 9 plots this dB loss for each layer up to a few more layers than the first half of this three-cavity filter. The second half is symmetric to the first half. It is clear that the effects are by far the greatest for the layers nearest the spacer (or cavity) layers. Such extreme situations are not expected in a real case where each subsequent layer termination would be attempting to cut at the next turning point and thereby compensate the foregoing errors.

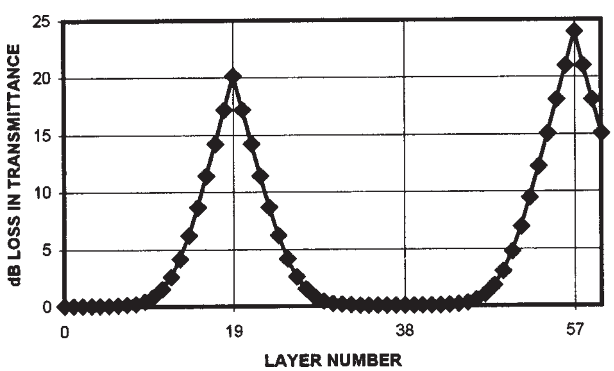

Figure 9: Average transmittance dB loss due to 2% QWOT errors by individual layer number.

We devised a scheme to calculate the change in reflection with change in thickness of a layer at the turning points. Figure 10 illustrates the principle. This is the reflectance amplitude circle diagram view of layer 5, 6, and 7. Each layer has a maximum and minimum reflectance as it crosses the real axis, i.e., the turning points. These define two points on the reflectance amplitude circle diagram which are on a diameter of the circular locus of that layer. The center of that diameter is the center of a circle for that layer which is not collocated with the center of the diagram defined by the intersection of the real and imaginary axes. An angle (shown by arrows in the figure) can be computed from this data which represents any given phase (QWOT) error from the turning point on the real axis. The change of reflectance from such and error point to the ideal turning point can be computed for this data. From this, we can calculate the expected error in ideal layer thickness as a function in the amount of reflectance change needed to sense a turning point. Figure 11 plots this turning point error sensitivity for the first 45 layers of this filter design. This can be seen to be intuitively consistent with Figure 5 where the cavity layer (19) termination changes appear more dramatic and thereby more sensitive than the next layer (20) termination, which is the worst sensitivity.

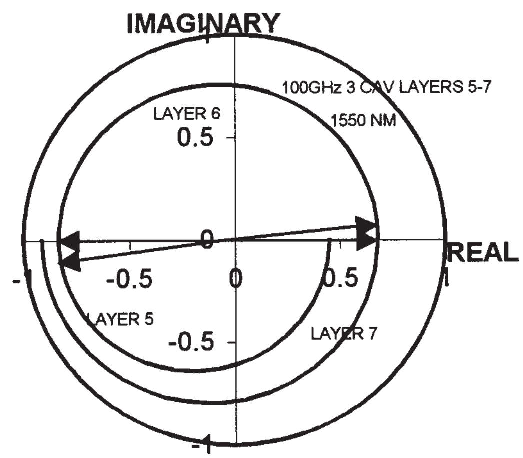

Figure 10: Reflectance amplitude circle diagram showing scheme to calculate the change in reflection with thickness of a layer at the turning points.

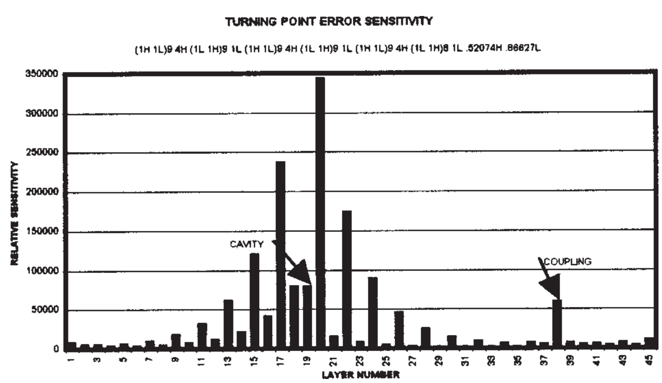

Figure 11: Relative sensitivity to turning point errors for each of the first 45 layers of this filter design.

The effect of errors on the T_{ave} as a function of layer position is estimated by the product of the data from Figures 9 and 11. This is plotted in Figure 12 and shows how critical the layers near the spacers can be. The coupler layer effects are almost invisible on this scale.

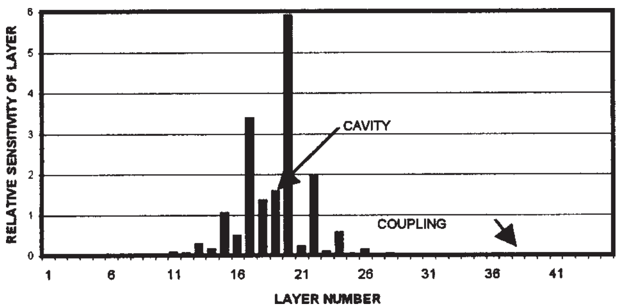

Figure 12: Overall relative sensitivity of the first 45 layers; the product of Figures 9 and 11.

When an error occurs in this type of monitoring, the best possible compensation for the effects of the error will be by attempting to cut each subsequent layer at its turning point. When we generated the data used in Figure 9, we then also reoptimized the thickness of the layer after the layer with the error. In every case, the T_{ave} was restored to the ideal value and that layer was terminated at the turning point. This shows that even an error at the most sensitive (worst) layer can be essentially totally compensated by the next turning point. The phase of all of the reflections except the layer with the error will be in perfect relationship. We have performed other simulations where the error was not corrected until a subsequent layer. 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}.

Even though compensation for errors is always at work, there are real 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 Figure 8. A realistic modeling of errors and compensation as it actually happens today has not been reported to our knowledge, but we are pursuing it.

CONCLUSIONS

We have provided equations to estimate the bandwith of DWDM filters at 0.3 and 20.0 dB as a function of: refractive indices, number of half waves in the spacers, number of layer pairs in the mirrors, and the number of cavities in the design. The effects of signal-to-noise ratio and monitoring errors have been shown. An estimate of the sensitivity of the average transmittance in the passband of a typical filter to errors in a layer versus its position in the design has been developed. It is clear that it would be impossible, with the current technology, to produce satisfactory DWDM filters without the “natural” error compensation features of the typical monitoring scheme.

REFERENCE

1. S.R. Schmidt and R.G. Launsby, *Understanding Industrial Designed Experiments*, Air Academy Press, Colorado Springs, 1994.