Simulation of errors in the monitoring of narrow bandpass filters

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Narrow bandpass filters are extremely sensitive to errors in the optical thickness of the layers, but they have an extraordinary inherent capability to compensate for these errors. Graphical examples of errors of differing magnitudes and types with and without compensation are shown with computer simulation of the optical monitoring techniques. This allows the estimation of what magnitude of errors may be tolerable in given applications. © 2002 Optical Society of America

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1. Introduction

The design and monitoring of narrow bandpass (NBP) filters such as might be used in communications dense wavelength division multiplexing (DWDM) through fiber optics, etc., has been previously described.[1,2] Those papers discuss the effects of noise in the optical monitoring signal and errors in the termination of the layers at their design thicknesses. The varying sensitivity of different layers in a typical design have also been discussed. Such a typical design might be represented by (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. The single design chosen here is specific to and relatively representative of DWDM, which is the specific thrust of the paper. There are a broad variety of optional designs for DWDM. The point here is to illustrate graphically what should be necessary and sufficient for the practical application of such filters. The effects in other designs and applications should show the same general behavior. A realistic modeling of errors and compensation as it actually occurs in practice with DWDM filters has apparently not been reported in detail. Zhou et al.[3] briefly reported research of this type with limited conclusions. In the present research, the effects of random errors in layer termination are simulated and shown graphically, with and without the natural error compensation properties of the commonly used monitoring technique. Simulations are shown at various magnitudes of layer optical thickness error to allow the estimation of what level might be tolerable for given applications.

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2. Narrow Bandpass Filter Monitoring

The requirements for a typical NBP filter for DWDM have been illustrated.[1,2] A three-cavity filter design as given above has 114 layers. One major criterion in the quality of a DWDM filter is the decibel loss within the transmittance passband. Losses are usually required to be less than 0.3 dB in the passband of approximately 0.35 nm for a 100-GHz filter. The most critical layers for monitoring errors have been shown[1] to be near the spacer or the cavity layers. The monitor signal decreases 2 orders of magnitude from the starting layer to the spacer layers, and this further exacerbates the sensitivity to errors. The sensitivity of these filters to random-thickness errors in the layers is striking. Figure 1 shows the results of 20 cases with random errors of 0.01%. Compared with a typical specification of no more than 0.3-dB loss in the passband of 1550 nm $\pm$ 0.175 nm, it can be seen that 0.01% random errors totally destroy the yield of useful filters for these applications, both by the in-band losses and by the position of the rejected wavelengths. The use of 20 cases in these figures seems adequate to eliminate fluctuations in the statistical result without obscuring the shapes of the individual results from errors. Random (uncompensated) errors as in Fig. 1 but of 0.002% magnitude are shown in Fig. 2. This magnitude might generally be satisfactory with respect to the typical requirement. There are approximately 3 orders of magnitude between the 0.002% and the 2% to 4% errors that a

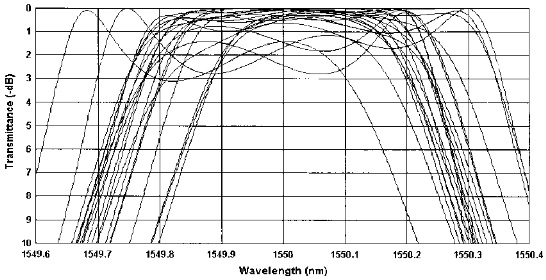

Fig. 1. Uncompensated random errors of 0.01% in the optical thickness of layers in the 114-layer, three-cavity filter given in the text. Note that transmittance scale is 10× that of Figs. 2–7.

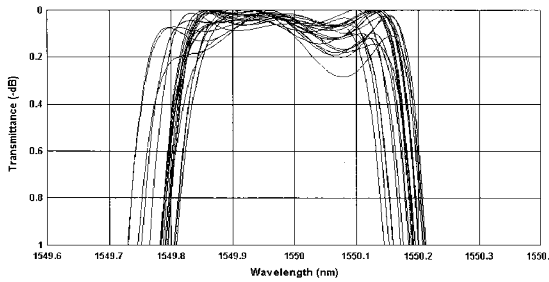

Fig. 4. Effects of errors of 4% with compensation as in Fig. 3.

human operator might be expected to achieve on layer terminations.

When the common monitoring technique of terminating each layer at the turning point is used, errors from previous layer terminations are largely compensated.[1,2] When an error occurs in this type of monitoring, attempting to cut each subsequent layer at its turning point is the best possible compensation for the error effects. This depends on monitoring a single part throughout the entire deposition at a wavelength in the center of the desired passband. These techniques have been described and analyzed some time ago by Bousquet et al.[4] Macleod[5] performed an extensive analysis of the technique and the effects of errors. He examined several variations of turning-point monitoring, such as second- and third-order monitoring, and showed that only the first-order monitoring at the passband wavelength was likely to be satisfactory. Macleod and Richmond[6] carried this research further to include the effects of dynamic errors such as a change of index after a layer is deposited. These dynamic effects must obviously be minimized for DWDM applications and seem well controlled by modern energetic processes such as ion-assisted deposition and dual-ion-beam sputtering. Regalado and Garcia-Llamas[7] also provided a general mathematical method for finding the relative stabilities of various types of coatings.

Figure 3 shows the effects of 1% random errors when this turning-point type of compensation is in effect, and Fig. 4 shows results for errors of 4%. The latter might be a reasonable upper limit on tolerable errors with respect to a 0.3-dB specification. Errors of 5% are shown in Fig. 5 and would probably not be satisfactory.

All the above cases are for random errors that are symmetrically distributed about the ideal turning point at the end of quarter-wave, optical-thickness layers. When we take the case of errors that extend from the turning point to greater thickness (long side), as might be more typical of an actual case, we

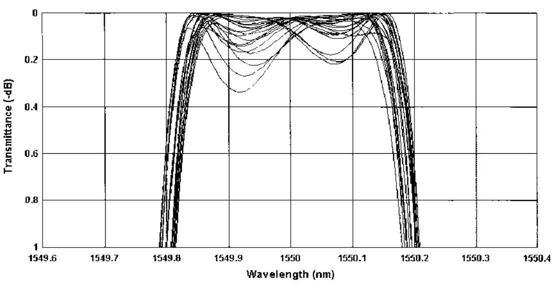

Fig. 2. Uncompensated random errors of 0.002% in a filter as shown in Fig. 1.

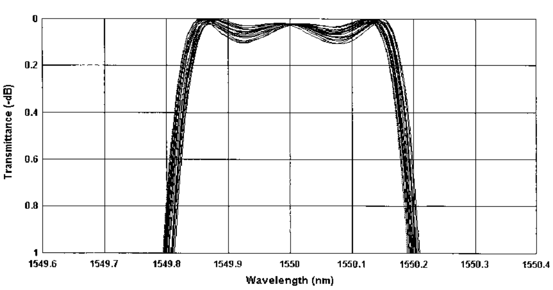

Fig. 3. Effects of 1% simulated random errors centered about the turning points when terminating the layers (monitoring) in a mode that provides compensation.

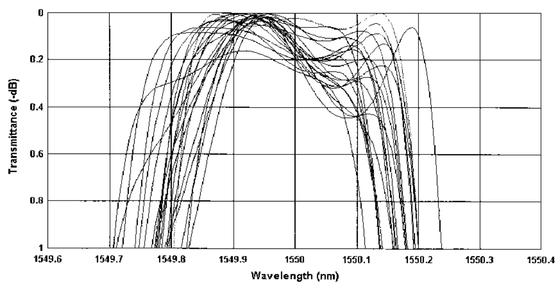

Fig. 5. Errors of 5% as shown in Figs. 3 and 4.

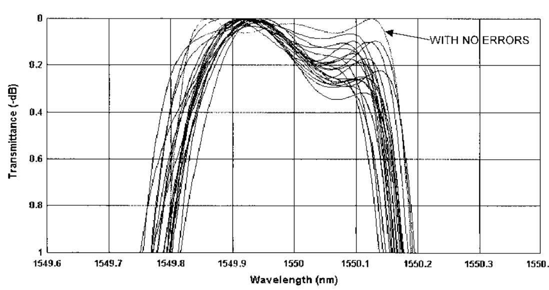

Fig. 6. Effects of 3% random compensated errors that extend only from the turning point to the greater thickness, for comparison with the results in Figs. 4 and 5.

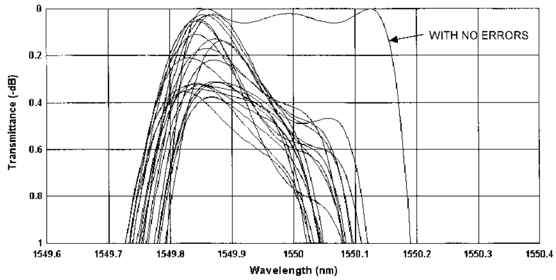

Fig. 7. Effects of 3% random compensated errors that occur entirely before the turning point, for comparison with the results in Figs. 6.

see the effects of 3% in Fig. 6 for comparison with the results in Figs. 4 and 5. On the other hand, when the cases of errors entirely before the turning point (short side) are simulated, the effects are as shown in Fig. 7. These short-side errors seem to have a more detrimental effect than the long-side errors. It seems that the potentially acceptable effects at 3% for long-side errors are best matched by the short-side errors of approximately 2.25%. An explanation for this difference has not yet been found.

3. Conclusion

The contrast between the effects of uncompensated random errors and the compensation of errors by attempting always to terminate at the turning points of the layers has been illustrated. There are 3 orders of magnitude between the 0.002% needed for good results with no compensation and the 2% or 4% needed with turning-point compensation. It is clear that the compensation effects are essential to practical NBP filter production. A curious difference in results has been found for errors that are entirely after the turning point versus those that are all before the turning point.

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