Non-turning-point monitoring improves narrow bandpass filters

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Historic practice has been to optically monitor narrow bandpass filters by the termination of each layer at a turning point. The problem is that turning points are the least sensitive points to the change of the optical signal with thickness and, thereby, those points are most prone to errors. It is shown that better performance in the production results can be achieved by designing and monitoring in order to terminate layers at non-turning points. A further advantage has been discovered wherein nonoptical monitoring of some layers is used to achieve even better stability in the production result. Simulation programs have been applied to such designs and demonstrate the advantages as compared to the historical approach. © 2009 Optical Society of America

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1. Introduction

Historically, narrow bandpass filters (NBF) have been optically monitored at the turning points (TP) of layers of quarter-wave optical thickness (QWOT) at the passband wavelength. This has been shown by Macleod [1] and also Bousquet et al. [2] to give very beneficial error compensation effects. The retention of these compensation effects when the layers are not terminated at the TPs is a key point of this work. It should also be pointed out that it is necessary to directly optically monitor the deliverable part in order to gain the maximum benefit of this error compensation. This is because any variation in the uniformity of the coating layers from the monitored point to other areas of potentially deliverable parts will vary the performance of the other areas versus the monitored point.

There is difficulty in terminating the QWOTs of the ideal design at exactly the TPs because the rate of change of reflectance with thickness goes to zero at the TP. A common practice has been to allow the monitor signal to pass the TP just enough to show a perceptible change in direction, as seen for two layers in Fig. 1. This is in effect the most common form of non-TP monitoring for NBFs. The overshoot in Fig. 1 is 0.2% transmittance (0.2%T) which represents a change on the vertical scale of 0.2% of T. A change of 0.1%T might be enough to sense the TP, if the noise in the signal was low enough, but 0.2% T is illustrated here to make the overshoot more apparent. When computer capability is included in a system, the derivative of the monitoring signal has been used by some practitioners to indicate the TP when the derivative goes through zero. Various other software systems have been employed, including that of Schroedter [3], wherein the monitoring signal is fit to the predicted TP curve to determine the termination of the layer. Which of these systems is used in any given automated optical monitor has not generally been disclosed. A. Zöller of Leybold Optics indicates that their experience with automatic monitoring is perhaps an order of magnitude better than the 0.2–0.3%T errors that will be investigated here to make the various effects more apparent.

2. Monitoring by Turning-Point Overshoot

Figure 2 shows the spectral curve of the basic three-cavity NBF to be studied in this work. Its design is (1H 1L)3 4H (1L 1H)3 1L (1H 1L)3 4H (1L 1H)3 1L
When random errors of 0.1%T are used without any overshoot, the results are as seen in Fig. 3. If various overshoots from 0.0 to 1.1%T are added to each TP in the design, Fig. 4 shows the results. There is a small increase in bandwidth (BW) and an increasing distortion of the shape of the top of the passband with increasing values of overshoot. This shape can be somewhat improved by adjusting the design thicknesses of the last two antireflection layers for the expected overshoot. This adjustment has been used in Figs. 5 and 6. Figures 5 and 6 show the simulated performance with a random error of 0.1%T for intentional overshoots of 0.1%T and 0.2%T, respectively. These figures show that the error compensation process is still effective, and they also show that the errors are reduced as the termination points move further away from the TPs.

The case of 0.3%T overshoot was also calculated, but is not shown here for brevity. Table 1 summarizes these overshoot results in its top three rows of data, with the %T overshoot in the first column, the QWOT thicknesses for high and low indices layers, the pass and optical density 3.0 blocking bandwidths, the monitoring type (optical versus hybrid, where physical/crystal monitoring is mixed with optical), the %T optical errors simulated, the %P physical errors simulated, the figure number where the results are illustrated, the reflectance average (Rave) percent of increase at the top of the passband due to random errors, and the spread in the edges of the band at 50%T due to random errors. Table 1 is as quantitative as practical, but the figures also give a better basis of comparison in some cases.

The fourth (bold) row in Table 1 is the basis of comparison where the 2:0:1 ratio (to be discussed below) shows the data for Fig. 3, with no overshoot, where the effects of errors are to increase Rave by 1.27% and the edge spread by 0.66 nm. When 0.1%T overshoot is used as in Fig. 5, the Rave drops to 0.339% with an edge spread of 0.34 nm; and for the 0.2%T overshoot of Fig. 6, Rave drops further to 0.163% with an edge spread of 0.25 nm. The 0.3%T overshoot case (not shown in a figure) starts to increase Rave again to 0.506% with an edge spread of 0.20 nm. The Rave is probably not so much due to random errors as the shape distortion seen in Fig. 4. The 0.3% overshoot case is better than the 0.2% case in edge spread, showing that edge control is improved by increasing overshoot even if the passband...
top shape is not. It can be seen that this planned overshoot method of non-TP monitoring, which has been used for decades, is simple and effective.

3. Another Non-Turning-Point Monitoring Scheme

Another concept was reported on the design and monitoring of NBFs at non-turning points by Willey [4,5], which offered error reduction potential with respect to the commonly used TP monitoring. Zöller, et al. [6] reported on a simulation program to evaluate the factors that influence the results of an optical coating production run. That program and an independent in-house simulation software by the author were used to evaluate the expected behavior and performance of the new designs with respect to the historic approaches. The results of the two totally independent simulations were shown to agree [7].

The new design approach here is to keep the optical thickness of each layer pair in a NBF design at one-half wave of optical thickness of the NBF wavelength, but to change the relative thicknesses of the high- and low-index layers to the overall thickness of the layer pair. A conventional NBF would have equal QWOTs of high and low index to give a ratio of 2:1 between the overall layer pair thickness and the thinnest individual layer. Typically the high-index layers were made thinner (but the same could be done with the low-index layers instead) to test designs with ratios of 2.67:1, 3.2:1, and 4:1. Figures 2 and 7 show the passbands and blocking bands of the 2:1 and 4:1 designs; the 2.67:1 and 3.2:1 designs give similar intermediate results. Details are found in Ref. [5]. The width of the passband and blocking band change with the ratio, but this can be adjusted in the design to give the passband and blocking-band values as needed.

Figure 8 shows the total optical monitoring trace of such a 4:1 design of a three-cavity NBF with 42 layers, as used in this work. The design of this NBF is (0.5H 1.5L)3 3.632H (1.5L 0.5H)3 1.345H (0.5H 1.5L)3 3.632H (1.5L 0.5H)3 1.19989L 0.96265H 0.90522L at 550 nm. The high-index layers are thin in this case (except the three spacer layers) and the low-index layers have two turning points in each layer, but the termination points are not at the turning points. The key principle of this approach is to terminate the layers away from the TPs where the error in %T of the termination will cause a smaller error in layer thickness than would occur at a TP termination. The benefits of error compensation are retained here as in conventional NBF monitoring.

<table>
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<tr>
<th>Ratio or %T Overshoot</th>
<th>QWOT L</th>
<th>QWOT H</th>
<th>Passband Width</th>
<th>Block-Band Width</th>
<th>Monitor Type</th>
<th>%T Error</th>
<th>%P Error</th>
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*aSee text for more detail on headings.*
Figure 3 shows the results of 10 simulations of a conventional (2:0:1) TP monitored NBF of a similar three-cavity and 42-layer design where the random errors in layer termination were 0.1%T. The design of this filter is given above. The last two layers of this design and the two coupler layers were physically (P) monitored, but no random errors were added to these layers in this case. The layer errors were a random distribution over ±0.1%T.

4. Non-Turning Point Design Procedure

The design procedure used for this new non-TP monitoring design starts with a single cavity modified from the 2:1 design to have the ratio desired, such as 4:1. Such a starting design at 550 nm might be (0.5H 1.5L)3 4H (1.5L 0.5H)3. The peak of this passband would no longer be at 550 nm. The thickness of the spacer/cavity layer (4H) would then be adjusted until the peak was restored to 550 nm. A two-cavity filter would then be made of two copies of this stack separated by a coupler layer, such as (0.5H 1.5L)3 3.632H (1.5L 0.5H)3 1.0L (0.5H 1.5L)3 3.632H (1.5L 0.5H)3. The peak of the passband would again be displaced from 550 nm. The coupler layer thickness would then be adjusted to restore the peak to 550 nm. This result would then be replicated to provide a three-cavity design, such as (0.5H 1.5L)3 3.632H (1.5L 0.5H)3 1.345L (0.5H 1.5L)3 3.632H (1.5L 0.5H)3 1.345L (0.5H 1.5L)3 3.632H (1.5L 0.5H)3. The last group is then broken out to be (1.5L 0.5H)2 1.5L 0.5H and a last layer of 1.0L is added. The whole design would then be optimized with only the last two or three layers as variables and perhaps 11 or more targets of 100%T in the top of the passband from 546 to 554 nm. These last two or three layers provide the antireflection (AR) coating for the NBF. It may be necessary to further refine the spacer and coupler layer thicknesses to restore the peak to be centered and symmetrical at 550 nm, if the AR perturbs that result.

5. Non-Turning Point Monitoring

The distances of the termination points from the TPs increases with the layer ratio and, thereby, the potential improvement in the termination accuracy. At the lower ratios, such as 2.67:1, an accumulation of layer errors can cause a TP to be reached sooner or later than expected. When this happens, the monitoring may break down and fail to track properly for the rest of the layers. It has since been shown possible to make the algorithms of the software capable of dealing also with these problems during monitoring, but the software used for this work did not yet have that...
capability. When the ratios are larger, larger errors can be accommodated without causing a monitoring breakdown. Figure 9 shows the $2:67$ ratio case with $0.1\%$ optical errors and $0\%$ crystal error. One of these 10 simulations has a major monitoring breakdown and most of the rest have significant breakdowns. It is apparent that a larger ratio would be needed for more robust results than found with the $2:67$ design. The design of this NBF is $(0.75H \ 1.25L)^3 \ 3.8125H \ (1.25L \ 0.75H)^3 \ 1.185L \ (0.75H \ 1.25L)^3 \ 3.8125H \ (1.25L \ 0.75H)^2 \ 1.25L \ 0.48297H \ 0.6592L$.

Figure 10 shows that a $3:2:1$ ratio would give excellent results for $0.1\%T$ and $0\%$ crystal errors. The design of this filter is $(0.625H \ 1.375L)^3 \ 3.7325H \ (1.375L \ 0.625H)^3 \ 1.168L \ (0.625H \ 1.375L)^3 \ 3.7325H \ (1.375L \ 0.625H)^3 \ 1.168L \ (0.625H \ 1.375L)^3 \ 3.7325H \ (1.375L \ 0.625H)^2 \ 1.15334L \ 1.04597H \ 1.06385L$.

Figure 11 shows that $0.3\%T$ and $1\%$ crystal errors would start to have some monitoring breakdowns and this is, therefore, probably beyond the range of errors that would be chosen for stable production. The power of the new approach starts to become more evident in Fig. 12, where $0.1\%T$ and $0\%P$ gives a far better result than the conventional TP monitoring seen in Fig. 3 and even the $0.2\%T$ overshoot shown in Fig. 6 with the same errors. This design has a noticeably wider passband than the $2:0:1$ design, but the design could be adjusted to give similar results. To further illustrate the robustness of the approach, errors of $0.3\%T$ and $3\%P$ are seen in the $4:1$ design shown in Fig. 13.

6. Nonoptical Monitoring of Some Layers

The thickness of the thinner layers in these designs becomes less with increasing design ratio. This will cause the absolute value of percent thickness errors caused by crystal/physical ($%P$) thickness monitoring to become less with increasing ratios. This adds an advantage to higher ratios. Here, it is assumed that the percent thickness errors in crystal/physical monitoring are independent of layer thickness, but this may or may not be a totally valid assumption. Nothing quantitative and statistically significant has been found in the literature on this subject. Some have expressed the thought that quartz crystal monitor (QCM) errors are random absolute errors of the order of $0.5$ to $1.0$ nm, more or less, independent of thickness, and that an additional several percent physical thickness variations may be due to process and equipment variations.
It was somewhat surprising to find through the simulations that physical thickness monitoring of the thin layers in some cases gave more stable and reproducible results than all-optical monitoring. If, in fact, the errors in physical thickness monitoring tend to be a constant percentage of the layer thickness, then the absolute errors would be reduced by reduced layer thickness. When the thin layers are optically monitored, the termination %T is determined from a percentage of the minimum and maximum found in the previous layer. For some as yet undetermined reason, this is inferior to the physical termination of the thin layers in some cases.

Figure 14 shows the 2:67 design with hybrid monitoring having 2% physical thickness errors and 0.2%T errors. This is considerably better than the results of the conventional monitoring seen in Fig. 3 with errors of 0.1%T and 0.0%P, respectively. Figure 15 shows that the 2.67:1 design only starts to have breakdowns with 3%P and 0.3%T optical errors.

Figure 16 illustrates that the 4:1 design has very good performance at 1% physical thickness errors and 0.1%T errors. Figure 17 shows that even 4% physical errors and 0.5% optical errors give results which are comparable to the 0.1%T and 0%P results of the conventional monitoring shown in Fig. 3.

7. Discussion

Table 1 summarizes the results of this work as quantitatively as practical. The first three rows of data are for the long-established non-TP monitoring method of overshooting the turning point by a small amount. The last nine rows of data are for the new methods. The last two columns show the comparative increase in the Rave over the error-free design at the top of the passband and the average spread in the edge width range with errors. These columns plus the figures with the various levels of errors and overshoots give the most interesting results of this work. The changes in passband and block-band widths can be seen for each design.

The overshoot monitoring appears best at 0.2%T overshoot or less for the top of the passband shape, but more overshoot is best for the spread of the edges. Overshoot non-TP seems to be practical at the levels of signal to noise that might be expected in optical monitors. This shows a major improvement over attempting to cut as close as possible to the turning point.

The new method shows that it can be made to give similar results to the overshoot method in some cases. However, the passband and blocking-band widths may need to be adjusted by redesign. It appears that ratios of 3:0:1 or greater may be advisable to avoid monitoring breakdowns in the presence of errors. Straight non-TP optical monitoring (not hybrid) gives even better results than the overshoot method in terms of increasing the Rave and reducing the edge spread from the design due to errors. The hybrid method allows even larger errors in both %T and %P without risking monitoring breakdown.

8. Conclusion

The commonly used turning-point overshoot method of optical monitoring of NBFs has been simulated and given some quantitative basis. Independent simulations have shown that the new optical and hybrid non-turning-point monitoring of a NBF can be designed and used to improve the performance of the resulting filters in production by a factor of
several times. The hybrid approach of monitoring the thinner layers by physical thickness makes it possible to use ratios nearer 2:1 and thereby preserve the narrower passband and wider blocking bands of the conventional 2:1 TP monitored approach. The choice of ratio will be driven to be large enough for robust monitoring, but that will be tempered and traded with the blocking bandwidth needed for the NBF in question. In practice, the overshoot method might be preferred over the new methods except where there are optical advantages, such as angular performance, or physical advantages, such as stress control, to be gained by other than the common 2:1 ratios.

References