Monitoring thin films of the fence post design and its advantages for narrow bandpass filters

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A fence post design, when viewed on a plot of index of refraction versus film thickness, has thin (usually of equal thickness) high-index posts that stand above a broad low-index ground. Monitoring fence post and related posthole designs offers error compensation and error reduction. There tend to be two or more extrema within the optical monitoring trace of each layer between the fence posts that aid in the calibration and control of film thickness. This also leads to a potentially improved control during deposition of narrow bandpass filters that have been designed with nonquarterwaves at the passband wavelength. © 2008 Optical Society of America

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1. Introduction

The concept of the fence post design was recently introduced [1] and that research followed from the previously discussed [2] new understanding concerning harmonic blocking bands. The name fence post results from the appearance on index versus thickness plots of narrow vertical posts of identical thicknesses of high-index layers above a ground of low index as seen in Fig. 1. The complementary posthole design would be as in Fig. 2 where the identical thickness low-index layers look like holes in the high-index ground.

Index profiles such as those in Fig. 1 have been employed by Schulz *et al.* [3,4] for hard, scratch-resistant antireflection (AR) coatings on plastic. There, the thick low-index SiO_2 layers separated by thin TiO_2 layers are key to the hardness and scratch resistance. This same principle might be useful for other classes of coating, and it has been shown [1] that essentially all classes of coating can be reasonably approximated with the technique of identical thin layers (usually high-index fence posts) spaced by thick layers of the opposite index. The posthole version might be advantageous in cases for which the minimization of physical thickness is important or in which polarization changes with angle are to be minimized as shown in Ref. [1]. The thin layers do not have to be all the same thickness, but that simplifying factor will be used here.

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2. Monitoring and Control

The design for monitoring and control of fence post and related designs in actual fabrication and production is the subject of this paper. There appear to be some advantages to monitoring these designs compared with other basic designs such as quarter-wave optical thickness (QWOT) stacks. This study is confined to examples of narrow bandpass (NBP) filters, but the principles are equally applicable to all other types of design as shown in Ref. [2]. Figure 3 shows the spectral result of the conventional NBP design, and Fig. 4 shows the entire predicted optical monitoring trace at 550 nm, which is in the middle of the passband. This design is sub (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 is referred to as a 2:1 design because the ratio of the overall optical thickness of a layer pair to its thinnest element is 2:1. All the layers are terminated at turning points except for the two coupler layers and the last two antireflection (AR) layers that would likely be terminated by quartz microbalance (QMB) or by time-power techniques.

Figure 5 shows the spectral result of a 108 layer NBP of the fence post design. This design is sub

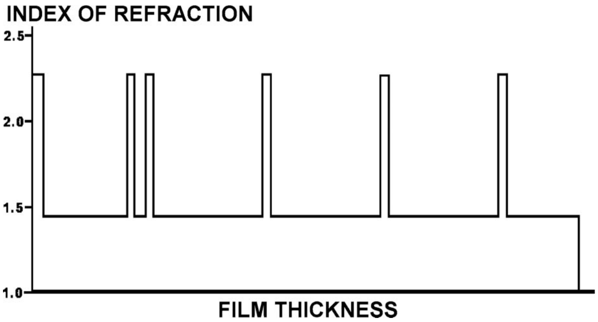

Fig. 1. This thin-film design appears to be fence posts of high-index layers above a low-index ground.

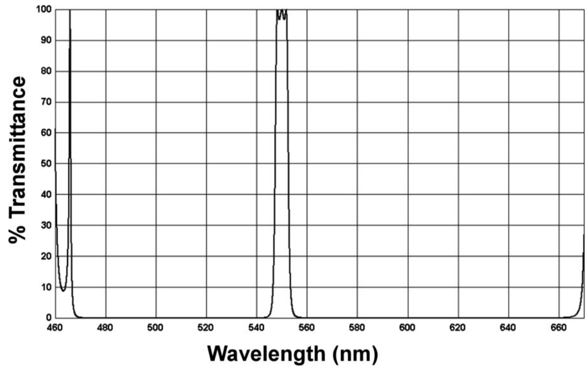

Fig. 3. Spectrum of a conventional NBP filter.

(0.2H 1.8L)8 0.2H 2.75L 0.2H (1.8L 0.2H)8 1.74L (0.2H 1.8L)8 0.2H 2.75L 0.2H (1.8L 0.2H)8 1.74L (0.2H 1.8L)8 0.2H 2.75L 0.2H (1.8L 0.2H)7 1.8L 0.50651H 1.39599L air at 546.75 nm by use of the materials listed above. This design would be referred to as a 10:1 design, as explained above. Figure 5 also shows that the blocking bands are narrower for the 108 layer fence post design, and this shows that more layers are needed to achieve the same optical density of blocking. This might be a disadvantage unless there were a benefit to having the passbands near 490 and 630 nm.

Figure 6 shows an expanded view of the monitoring trace for the last cavity of this fence post design including the last coupler layer and the last two AR layers. Figure 7 further expands the predicted monitor trace for the last six layers of the Fig. 5 design. Layers 103 to 106 are two typical layer pairs that have a total of two quarter waves of optical thickness (QWOT) at 550 nm but are not the usual one QWOT of high-index and one QWOT of low-index material. Layers 107 and 108 are AR layers to optimize the transmittance in the 550 nm passband; they are not QWOTs and do not total two QWOTs.

The thin high-index layers might be monitored either by a QMB or by time and power control of the high-index deposition source because these thin layers are not well suited to optical monitoring. The thick (low-index) layers are optically monitored here with relatively stable and precise layer termination by the "Last max-min cut technique" [5]. As seen in Fig. 7, the low-index 104th layer is terminated at 26.8% of the change in transmittance from the last maximum to the last minimum (366 units, $0.268 \times 366 = 98$ units) up from the last minimum. This technique has the advantage that the absolute photometric values do not need to be known, only the relative calibration of the number of units between the last two extrema. The computer control or the operator need only observe the number of units between extrema, make a calculation of the number of units to provide 26.8% of that, and terminate the layer to stop at 26.8% up from the last extremum. The technique has the further advantage that the change in units per change in film thickness is more sensitive and easy to determine than at a turning point, which should lead to more accurate layer terminations. Layer 106 is similarly terminated at 28.1% from its last max–min.

A key to monitoring fence post designs is that the thick layers have at least two extrema to facilitate the use of the percentage of the last min–max cut technique. In more general designs than NBP filters, the choice of monitoring strategy and wavelength tends toward shorter wavelengths in the band of interest to provide at least two extrema and because the longer wavelengths tend to follow with the proportionately smaller effects of the physical thickness errors because of the longer wavelengths. Layer 107 of Fig. 7 shows a case of a layer with only one extremum in the layer as monitored. No problem has been found by

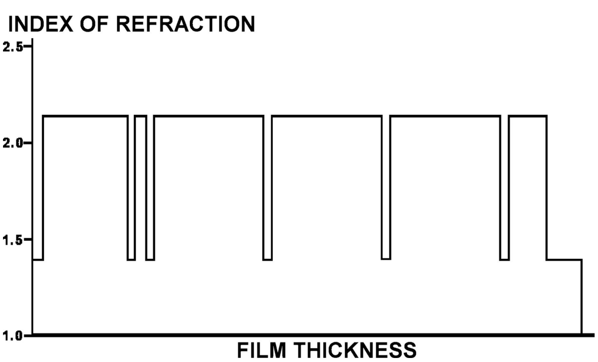

Fig. 2. This thin-film design appears to be postholes of low-index layers below a high-index ground.

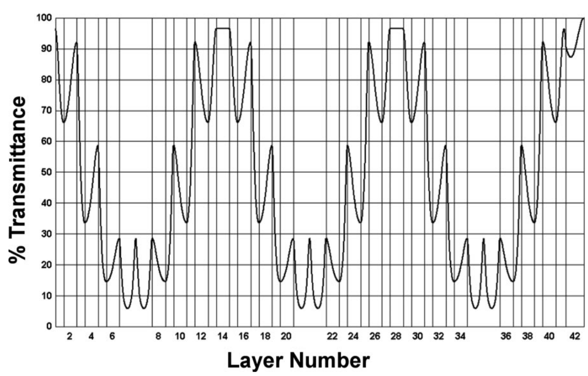

Fig. 4. Predicted optical monitor plot at 550 nm of all 42 layers of Fig. 3.

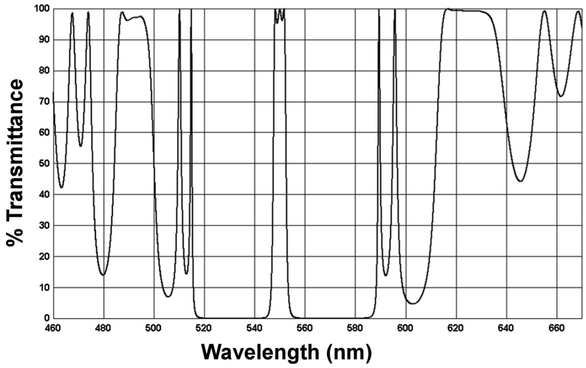

Fig. 5. NBP filter of the fence post design.

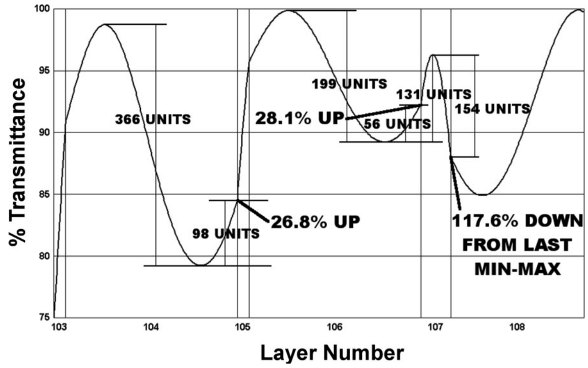

Fig. 7. Monitor trace for layers in the last cavity of the design in Fig. 5 with annotation for the percentage of the last max–min monitoring.

use of the last extremum of a previous layer with that of the current layer to calculate the up or down percentage as in Fig. 7. This 107th layer shows a case in which the termination is 117.6% of the distance in transmittance between the last maximum and the last minimum applied in a downward direction of transmittance from the transmittance level of the last maximum. To terminate at percentages of max–min greater than 100% has not created additional problems. In this case, layer 107 is a high-index layer, which is thicker than the rest of the high-index layers in the design, and it can be terminated by optical monitoring. The last two layers could also be terminated on the basis of averages of the actual crystal thicknesses or time-power values from previous layers.

Significant errors in the thickness of the thin fence post layers (high index in this case) can be tolerated because the termination point in the next layer will tend to compensate to make the combined layer-pair nearly the same as the design thickness. This should have the same benefits of error compensation at the monitoring wavelength as in the classical turning point monitoring at the passband wavelength of a NBP filter. In the case of Fig. 5, the 550 nm region should be well controlled, and any corrected errors will have increasing effects at wavelengths increasingly longer and shorter than 550 nm. However, since the relative errors as a percentage of design thickness are less at longer wavelengths, the longer wavelengths should be even more well controlled.

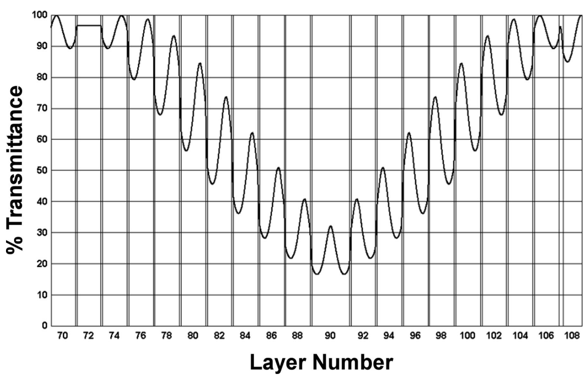

Fig. 6. Predicted optical monitor plot at 550 nm of the last cavity (layers 70–108) of the design in Fig. 5.

It has been found desirable to monitor optically all the designs of more than a few layers at a single wavelength on a single monitor chip with as direct a relationship to the deliverable parts as possible. This will generally be at the shortest wavelength practical in the band of interest (which would be in the passband for a NBP filter). The strategy allows the maximum possibility of a benefit of error compensation at the monitoring wavelength that is generally chosen for maximum error sensitivity. The correction will be best at the monitoring wavelength and the results of other wavelengths will follow in proportion to their proximity to the monitoring wavelength.

3. New Approach to Narrow Bandpass Monitoring and Control

The advantages of monitoring a fence post design can be gained in a nearly conventional NBP design by selecting a ratio that is greater than 2:1 to shift the layer termination points away from the turning points. The example of a 2.67:1 design is shown below. The closer the ratio is to 2:1, the closer are the blocking bandwidths and optical density in those bands to that of the conventional 2:1, but the termination points will also be closer to the turning points. This 44 layer design is sub (1.25H 0.75L)3 4.27H (0.75L 1.25H)3 0.86L (1.25H 0.75L)3 4.27H (0.75L 1.25H)3 0.86L (1.25H 0.75L)3 4.27H (0.75L 1.25H)3 1.4776L 0.16012H 1.38443L air, with the same ma-

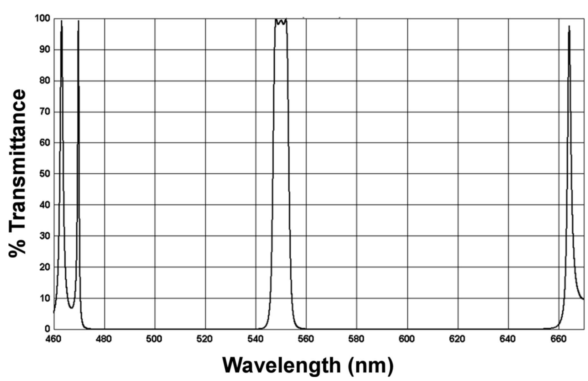

Fig. 8. Spectrum of a nearly conventional NBP filter.

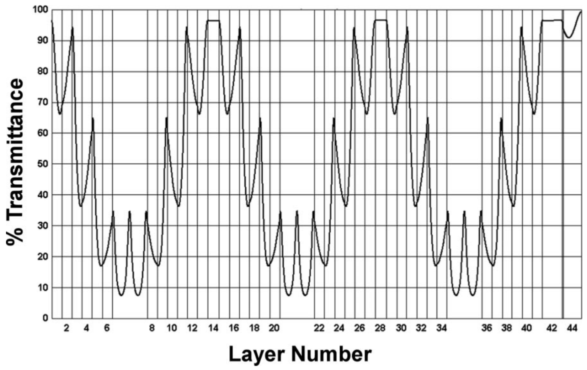

Fig. 9. Predicted optical monitor plot at 550 nm of all 44 layers of Fig. 10.

terials as above. Figure 8 shows the spectral plot that is very similar to that of Fig. 3. This has much broader blocking and fewer layers than the design of Fig. 5. Figure 9 shows the monitoring plot that is similar to that in Fig. 4.

The monitoring of the first four layers is shown in Fig. 10. The first layer is terminated at 9.1% up from the last max–min and includes the start point and the 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 from the next two max–min points. This design happens to have the thicker layers as high index, and therefore the max–min will be in the high-index layers. If the low-index layers were the thicker ones, the max–min would be in the low-index layers. The actual design choice would depend on other factors such as physical properties and angle sensitivities.

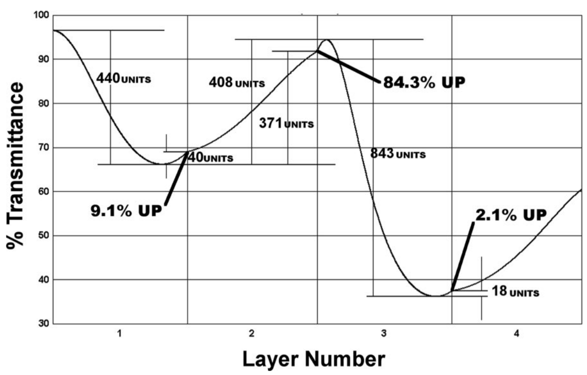

Fig. 10. Optical monitor plot at 550 nm of the first four layers of the Fig. 8 design.

4. Conclusions

Monitoring fence post designs offers the potential of error compensation and reduced layer termination errors because the layers are 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 layer between the fence posts, and this has a self-calibrating effect for each layer. A new design approach for monitoring NBP filters has been described that gives the potential for less fabrication and production errors to be gained by layer terminations at nonturning points while maintaining the benefits of error compensation at the monitoring wavelength.

It should be pointed out that that this new approach is more dependent on the stability of the monitoring signal from layer to layer than classical turning point monitoring. Some error could be introduced if the monitor's photometric scale drifted significantly with time, which would not be a problem with classical turning point monitoring. This would not, however, be expected to be a problem with most of the optical monitoring systems that this author has used.

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