Reliable production of steep edge interference filters

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ABSTRACT

Interference filters for spectroscopic purposes or sensor applications are characterized by strictly specified spectral blocking and transmitting regions with intermediate steep edges. These steep edges must be positioned within nanometer accuracy while the coating may consist of more than one hundred non-quarterwave layers. Though modern ion assisted deposition processes in conjunction with quartz crystal control are well suited for the production of complex filters, an optical monitoring device seems to be necessary to fulfill the demanding spectral requirements. Broad band optical monitoring (BBM) directly on the calotte has been employed to control the production of this type of band stop filters. For a large number of also different types of these coatings the BBM-technique demonstrated its capability to improve the reliability and flexibility in industrial production. Within a stable well-characterized deposition process error self-compensation effects allow for a fast realization of various designs within specified tolerances. Nevertheless, optical broad band monitoring could not be applied to all types of these steep edge filters because error propagation leads to unreachable solutions of the thickness tracing algorithm for specific cases. The given examples of complex steep filters and the corresponding post analysis of stored online spectra as well as the simulation of the monitoring process reveal the influence of the design itself to this occurrence. A suggestion for an identification of critical thickness values within the layer sequence is discussed and solutions to the problems are presented.

Keywords: optical interference coatings, broadband optical monitoring, band stop filters, precision optics

1. INTRODUCTION

The realization of complex oxide dielectric interference filters in automated manufacturing and industrial production environment usually requires insensitive and robust designs. The electron beam evaporation process, in conjunction with plasma ion assistance, offers the capability to produce stable, dense and shift-free films with highly reproducible refractive indices and low absorption. In many cases the thickness determination via quartz crystal monitoring at the calotte centre position yields sufficient precision. A certain error budget has to be taken into account which considers several effects like differing growth conditions or a varying particle distribution due to a changing shape of the evaporation plume.

Filters for special sensor applications or spectroscopic purposes, i.e. laser fluorescence microscopy, are types of long wave, shortwave, band pass or multiple band pass filters with very stringent specifications. The required spectral blocking regions and occasionally several high transmitting bands have to be separated by a transition zone which defines the width or steepness and the spectral position of the edges. These zones may be smaller than 1% of the design wavelength, while the optical density (OD = -log(T)) of the rejection bands may exceed OD5 and more. In many cases, these specifications are no longer accessible by pure quartz crystal control in a reliable way. Especially when the coating is only one processing step within a cycle of already prepared components reliability is an important fact.

To meet these demands it seems to be necessary to apply optical monitoring. Responding on the changing spectral characteristic it allows for taking advantage of error self-compensation effects. Thus this method is essentially capable to keep a certain spectral characteristic fixed on the wavelength scale.

Concerning the above stated filter types, many design solutions are accessible by thin film systems consisting of quarter wave optical thickness (QWOT) layers [1]. In this case optical single wavelength monitoring would be preferable. But this technique is affected by deficiencies in precision caused by instable geometrical factors, especially, when the monitoring witness glass is placed in the centre of the calotte. Additionally most applications require designs with a stop bandwidth, which may not be realized by a pure QWOT-system. These more sophisticated designs would need an elaboration of a suitable monitoring strategy first. And this means a loss in flexibility to get a fast and practicable solution.

One large advantage of the optical broadband monitor setup installed is its measurement position among the substrates of interest. Effects of an inhomogeneous thickness distribution along the radial position of the calotte are drastically reduced. The implemented tracing algorithm for determining the actual thickness has been demonstrated to be a suitable control mechanism for the realization of complex dielectric filters [2]. Depending on the process stability concerning the reproducibility of the material dispersion data, many designs can be accomplished by just loading the script and press the start button. But certainly there are several conditions conceivable for which this situation may not be given. One extreme example may be represented by a filter, which blocks the monitoring wavelength range completely. Here surely precision has to be cut due to the lower dynamic range of the CCD-device installed in the spectrometer system compared for instance to a photomultiplier detector.

The present paper tries to figure out which circumstances lead to a failure of this type of monitoring. Propagation of thickness errors may lead to a misinterpretation of the measured transmittance data causing severe deviations in thickness determination [3]. An understanding of this behavior can be utilized to install a simple test tool for checking design suitability. The presented coating examples show a design solution first which produces a non-quarter wave band pass filter in the straightforward manner mentioned above. This may be a good candidate to be the positive example. On the other hand a broad band-blocking filter seems to be suitable to be the negative example at the first glance. Calculation of the integrated gradual change in transmittance gives evidence of a manageable controllability by broadband-monitoring. The analysis of such a plot versus growing thickness gives a hint of the necessity to change the layer sequence of the design.

2. METHODOLOGY

2.1 Experimental

First the experimental set-up will be briefly explained. The principle algorithm that interprets the transmittance data is based on the well-known matrix formalism. The embedded discrepancy function can by visualized, which may give insight into the methods ability to determine correct thickness values.

The basic principle of the optical broadband-monitoring method in thin film technology has been already published in the 1980th for example in [4]. Further development towards the employed commercially available product considered in the present study has been done by the LZH[1]. The optical broadband-monitoring device installed consists of a fiber-coupled CCD-array spectrometer that is linked to the plant by a fiber, which collects light from a halogen lamp installed inside the chamber, and by a trigger-unit responsible for synchronization of the measurement cycles with the calotte rotation. The adaptation to the Leybold Syrus Pro plant has been realized within an implementation into the general steering software. The APS technology is used for ion assistance of the evaporation process. It is important to mention that stable process parameters are one requirement for a proper function of this optical control method. Particularly, the dispersion and absorption behavior of all materials involved have to be characterized very carefully.

The monitoring system compiles calibrated transmittance data for every revolution of the calotte. Each measurement will be utilized for calculating the thickness of the growing layer. The already deposited layer stack underneath will be assumed as correctly realized according to the design. Hereby an iterative algorithm finds the local minimum regarding the sum of the deviations modulus from the theoretical ($T_{THEO.}$) and measured ($T_{MEAS.}$) transmittance at every n available wavelength position λ_i. Thus the basic equation to be minimized is:

$$MSE = \sum_{i=0}^{n-1} \frac{1}{n} \left[T_{MEAS.}(\lambda_i) - T_{THEO.}(\lambda_i, d) \right]^2 . \qquad (1)$$

Here MSE stands for mean square error, and the variable parameter is the thickness d of the actual growing layer. An extrapolation towards the layer termination point is possible by taking several calculated thickness values into account.

From a practicable point of view the advantage of this method is its independence from any further information. But at a certain level of coating complexity additional information for reasons of stabilization may be helpful [5].

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2.2 Analysis and Interpretation

The determination of a minimum position by an iterative algorithm is easier when the minimization function shows a large gradient. Thus it can be recognized that the deviation of *T* with respect to *d* can by identified as a measure of reliability of the actual thickness determination. It follows from the equation (1):

$$\sum_{i=0}^{n-1}\frac{1}{n}\left[\frac{\partial T_{THEO.}(\lambda_i,d)}{\partial d}\right]^2 \approx \sum_{i=0}^{n-1}\frac{1}{n}\left[\left(T_{THEO.}(\lambda_i,d)-T_{THEO.}(\lambda_i,d+\Delta d)\right)/\Delta d\right]^2 = \sum_i \Delta T_i = \Delta T \qquad (2)$$

The quantity ΔT depicts the amount of change in transmittance from one traced thickness step to the next one with difference Δd . Thus a larger value of this sum means that the algorithm may easier distinguish subsequent thickness increments while comparing the online-measurements with theoretical values. Figure 1 illustrates such a change in transmittance schematically at two exemplary wavelengths showing that the differential quotient is the decisive quantity.

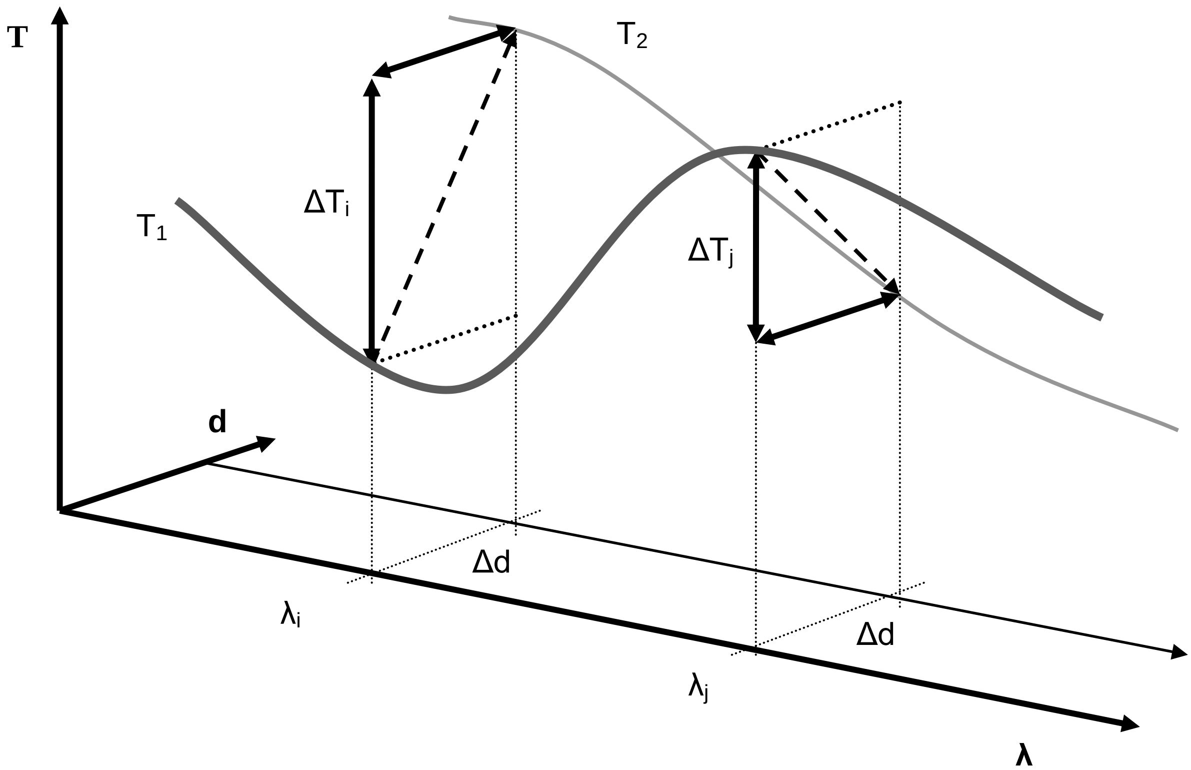

Fig. 1. ΔT is summed up by the infinitesimal changes in transmittance (from curve T_1 towards curve T_2) at two selected wavelength positions λ_i and λ_j due to the change in thickness Δd .

The interpretation of the resulting values of ΔT may be explained best within the framework of examples. Figure 2 demonstrates the ΔT -plot of a growing single high index layer of tantala on a B270 substrate. The step width for the thickness Δd is chosen to be a value of 0.6nm according to a typical deposition rate and time step between measurements. The monitoring range was 400nm to 1000nm. As expected, the beginning of the growing layer shows nearly no change in transmittance resulting in ΔT -values near zero. This behavior is consistent with the experience, when the coating process just started and the measured transmittance of the bare substrate does not seem to change at first.

Increasing thickness leads to a significant rise caused by a growing number of detailed spectral features of the single layer. The first minimum corresponds to the appearance of the first spectral turning point within the chosen wavelength range. In this case the minimum corresponds to 1QWOT@525nm. At this thickness value the spectral change remains nearly static, and after this point almost the complete spectrum seems to slowly rise again. It is imaginable that at this position the determination of the thickness is more error sensitive than at other thickness values. This fact clearly marks a crucial disadvantage compared to the single wavelength monitoring concept. The following maximum arises when the growing thickness passes 1QWOT@750nm where the transmittance reaches its second extreme position. It has also to be considered that the absolute value of ΔT depends on the magnitude of the materials refractive index. No significant differences towards the substrate refractive index will cause only small changes in transmittance.

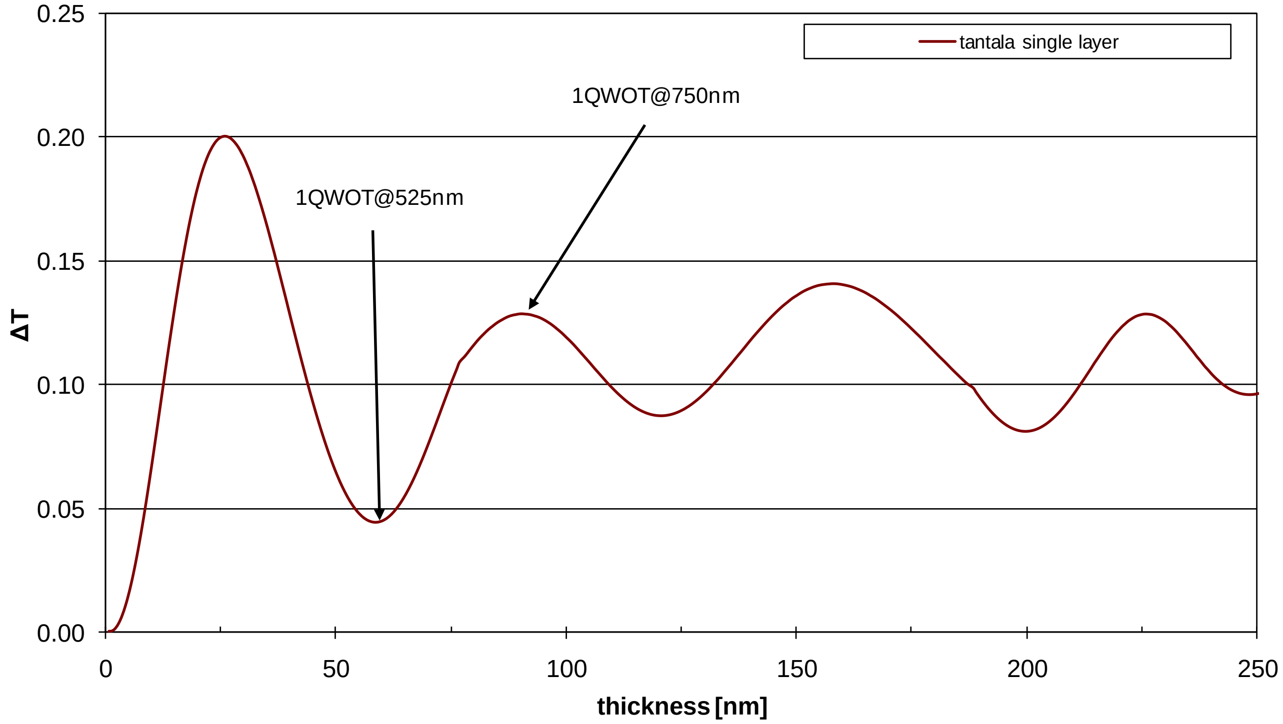

Fig. 2. ΔT (*d*)-plot of a growing high index single layer on a B270 substrate with step width 0.6 nm. The magnitude of the quantity depends on the materials refractive indices and its course is also effected by the chosen wavelength region (here: 400-1000nm). The marked extreme positions correspond to 1QWOT at 525nm and at 750nm respectively.

Further examples will be given in the next section in conjunction with results of more complex coatings.

3. RESULTS

As first example a band pass filter at 656nm is chosen. It is realized by a near QWOT-system with detuned cavities. The adaptation to the spectral requirements, especially the width and the smoothing of the pass region, led to a complete non-quarter wave design.

The illustration of the spectral changes of this 67 layer Ta_2O_5/SiO_2-system is given in Figure 3. ΔT rises up again in the first layer, and after the second one it does not fall short off a certain limit until the end of the complete coating. This level may be compared with values taken during the first layer. The spectral changes are at least as useful for a reliable thickness determination as they are after a growth of 6nm. And this thickness of a high index material starts to be well suited for identification by the broad band monitoring system.

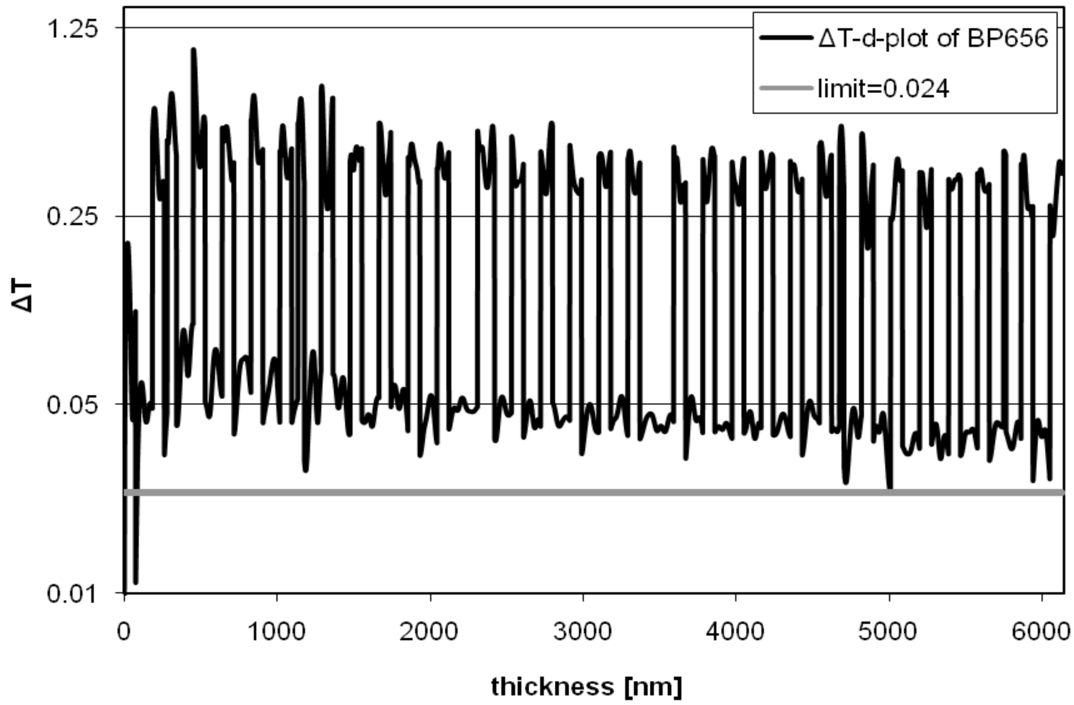

Fig. 3. $\Delta T(d)$-plot of the growing band pass filter. Strong differences between the materials are observable caused by the differing refractive indices. Still the graph does not fall short of a certain level.

Thus the coating should be controllable during the complete run and layer switching should be possible within sufficient precision. This statement may hold although neither measurement errors nor thickness errors due to statistical or cumulative effects are included in the representation. As suggested the filter could be manufactured successfully without any problems as demonstrated in Figure 4.

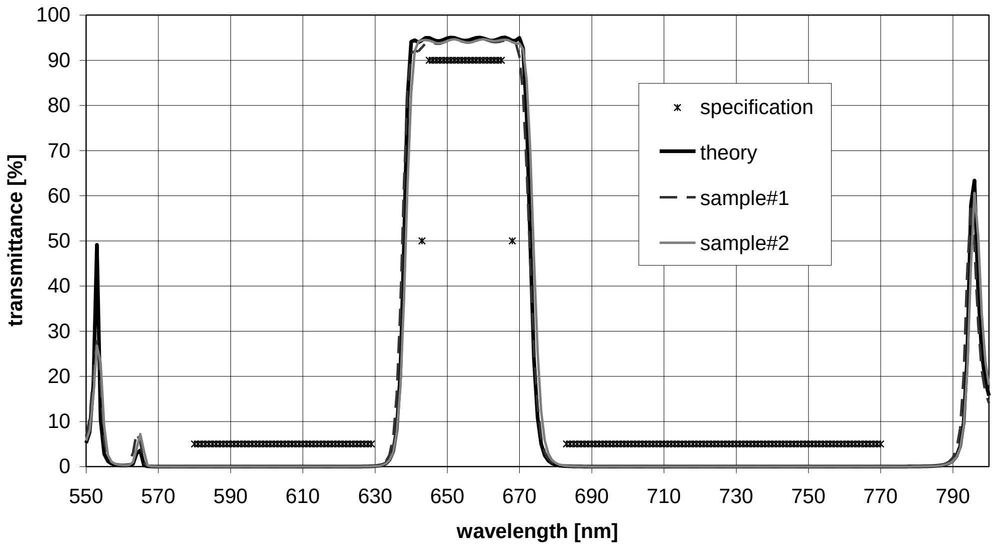

Fig. 4. Transmittance of two samples of the deposited band pass filter compared to the theoretical design target spectrum. The forecast of good reproducibility is fulfilled.

The second example does also deal with a band pass filter. But this one is specified at the wavelength 905nm which is near the edge of accessible wavelengths of the monitoring system. Additionally the complete visible and near ultra-violet spectral region has to be blocked, leading again to a complete non-quarterwave design.

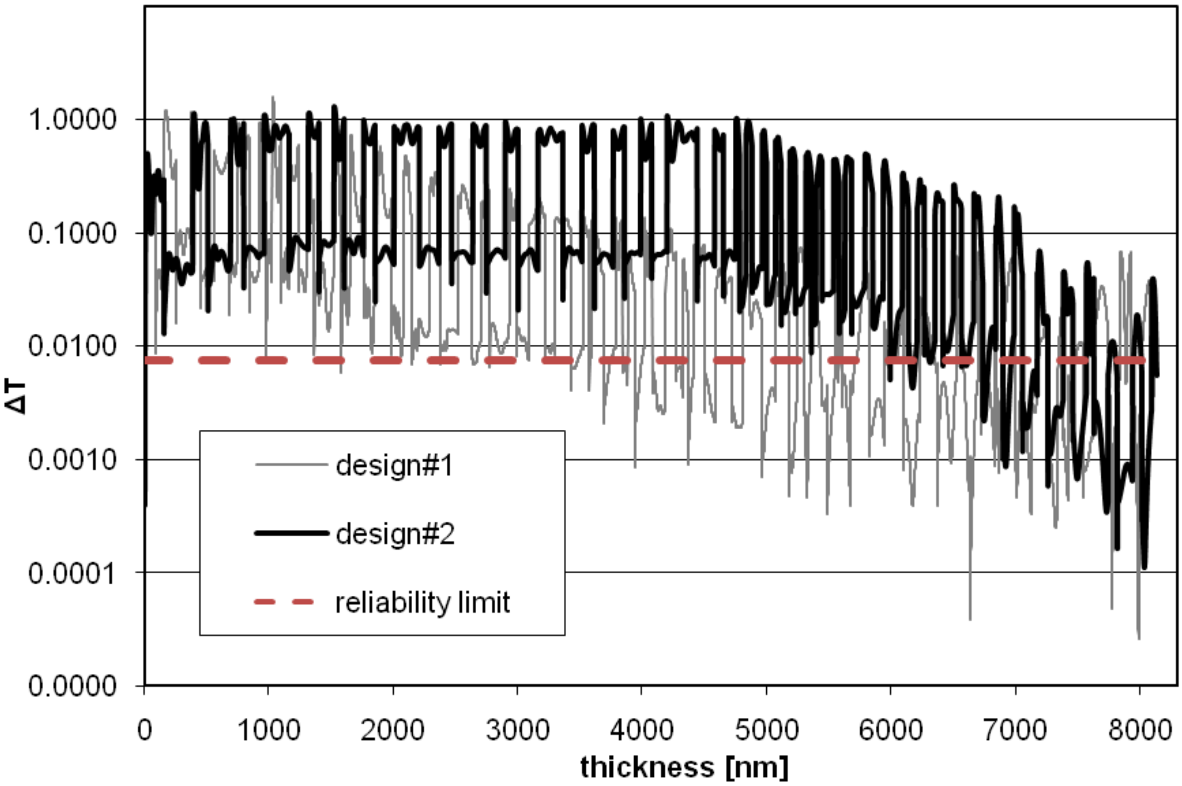

Fig. 5. Comparison of two ΔT (*d*)-plots for two different TiO_2/SiO_2-designs of a 900nm band pass filter with a wide blocking region. At certain individual overall thickness values, very small ΔT values indicate that a thickness determination is not possible in a reliable way anymore.

In Figure 5 two different designs are analyzed, which produce quasi the same spectral band pass characteristics with also nearly identical overall thickness. The first design shows very small ΔT values already before reaching the half of the complete filter and fall short of a reasonable limit already in an early stadium of the developing filter. For example the level of 0.008 is reached at 3500nm of 8200nm total thickness, which corresponds to the 32^{th} of 89 layers, respectively. In fact, it has been almost impossible to get a satisfactory result utilizing broad band monitoring in practice.

After restructuring the design, at least the last two microns of the coating show a low level of ΔT that is still manageable. Essentially the blocking from the green to the red spectral region has been shifted towards the end of the layer sequence. This action did result in a delayed suppression of significant spectral features. The new design fulfilled the specified requirements with 81 layers.

The corresponding transmittance diagram of the finally realized design no.2 is depicted in Figure 6.

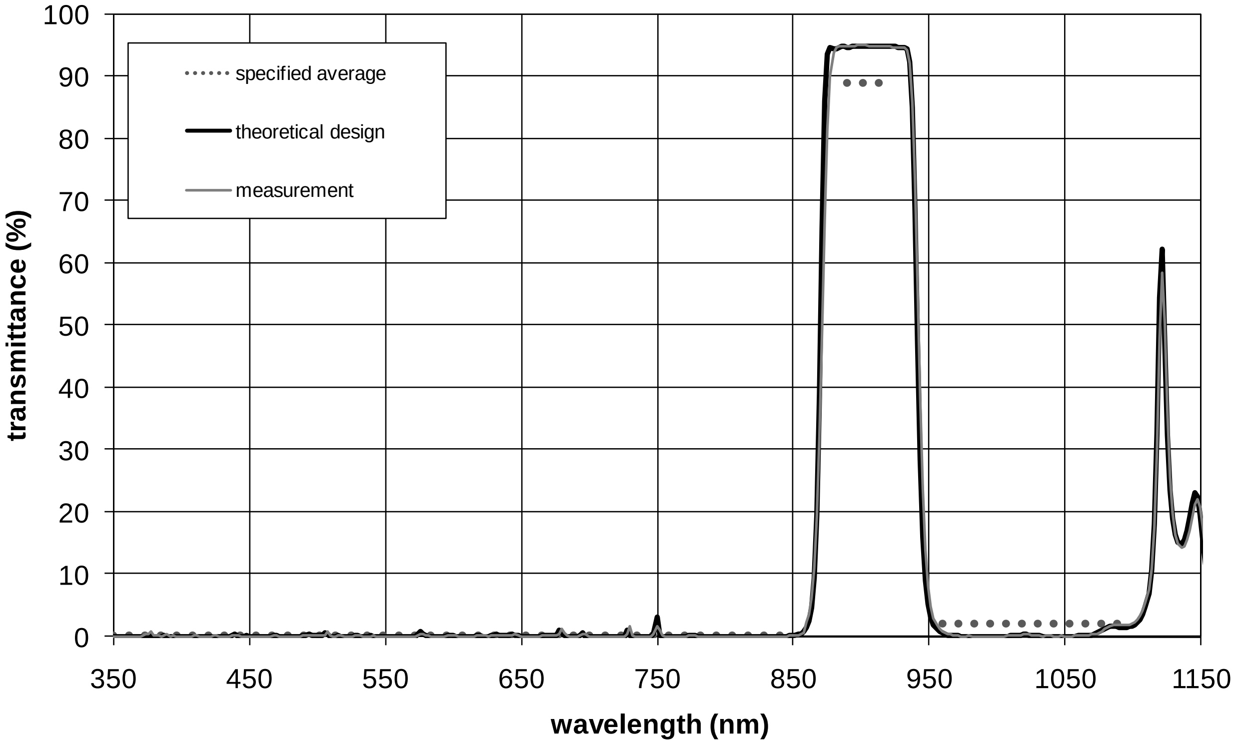

Fig. 6. Transmittance of the adapted 900nm band pass filter design compared to the theoretical design target spectrum. After analyzing a first design approach a necessary restructuring could be identified.

The agreement of the measurement with the target theory curve demonstrates that thickness errors are almost negligible. As a consequence of sufficient changes of the transmittance during the coating and especially at the end of each layer the algorithm is capable to determine the layer termination points with high precision.

4. CONCLUSIONS

The advantages of optical broadband monitoring directly on the rotating calotte are its measurement position itself, the ability to control the optical thickness, and the flexibility to realize a kind of rapid prototyping. By analyzing the mode of operation of the algorithm, which determines the layer thickness of a growing interference filter, explanations for a differing design dependent precision in thickness control could by illustrated. The preparation of the so called $\Delta T\,(d)$-plot allows for an estimation of the design suitability for a control by broadband monitoring. Sensitive layers, which may be difficult to control, or required design recalculations can potentially be identified. The analysis of a layer sequence by this tool makes a successful coating more predictable.

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