High performance Notch Filter Coatings produced with PIAD and Magnetron Sputtering

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ABSTRACT

For Notch Filters, Rugate designs with a small index contrast and apodisation are well known in the literature. The required deposition of gradient index layers or so called flip flop structures is very complicated and difficult to manufacture. Higher order H/L stacks of coating materials with high index contrast result in very thick layer stacks. In our approach we replace the second refractive index by equivalent layers consisting of H/L materials with high index contrast. This leads to a combination of thick (>100nm) and very thin layers. Stable coating processes with dense layers are strict requirements. Another challenge is the accurate thickness control of very thin layers in the nanometer range. Single notch filters were produced with PIAD and broad-band optical monitoring. The most challenging filters were demonstrated with magnetron sputtering and monochromatic optical monitoring. Some outstanding results of single and multiple notch filter coatings will be presented.

Keywords: Notch Filter, equivalent layer, magnetron sputtering, PIAD

1. INTRODUCTION

Increasing laser applications in many fields like life science, medical science, spectroscopy, metrology, basic research are leading to a strong demand of thin film components with extreme filter characteristics. One of the most challenging filters are single- and multi-Notch Filters (SNF, MNF) for fluorescence- and Raman spectroscopy. The challenge is the production of these complex and extreme filter designs with high precision and high reproducibility, high layer quality, low particle-/defect level, reasonable film stress and low manufacturing costs (cost per piece).

Rugate designs with a small index contrast and apodisation are well known in the literature. The required deposition of gradient index layers or so called flip flop structures is very complicated and difficult to manufacture and economically not successful. Actually hybrid designs of gradient layer and H/L-stack or QWOT-H/L designs with higher order and/or multiple thickness ratios and apodisation are used to narrow the blocking bandwidth for commonly used coating materials with high index contrast. This results in very thick layer stacks especially if small and deep blocking ranges are required. Such SNF and MNF are typically produced by ion beam sputtering which results in a very long deposition time by both the thick layer stack and the low deposition rate of ion beam sputtering.

Our approach with equivalent layers for the second index leads to relatively thin layer stacks and the used deposition techniques PIAD and plasma assisted reactive magnetron sputtering (PARMS) lead to a reasonable deposition time.

2. DEFINITION, DESIGN AND MANUFACTURING METHODS

2.1 NF definition

A notch filter is characterized by blocking or reflecting a specific and typically narrow range of wavelengths and passes light with high transmission on both sides of the blocking range. While a narrow band pass filter is well defined by the parameter ‘full width of half maximum’ (FWHM), the situation for a NF is more complex. A novel characterization of a NF is illustrated in Figure 1 and Figure 2. Figure 1 shows the typical characteristic of a notch filter with the narrow blocking range and the pass band from λ_1 to λ_2 as the range on both sides of the blocking range defined by the reference wavelength λ_0. The transmittance within the pass band has to be very smooth with a defined pass band

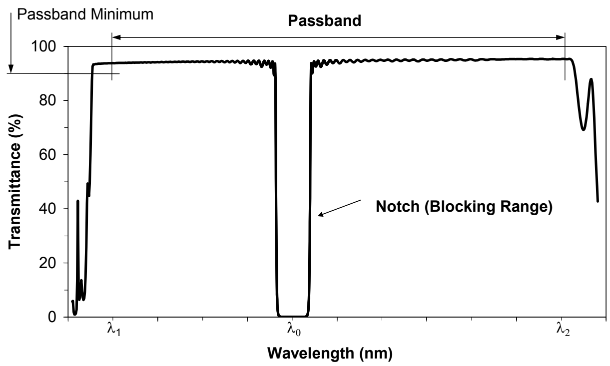

Figure 1 Single notch filter characteristic

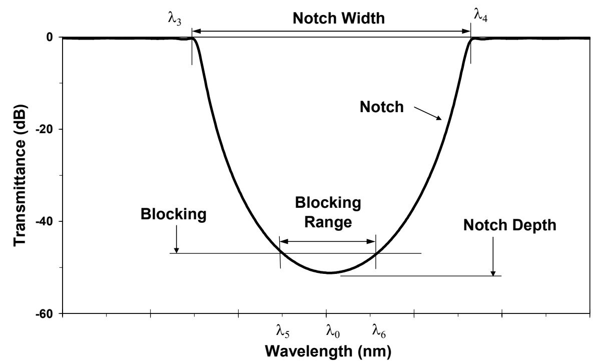

Figure 2: Definition of a notch filter characteristic

minimum. Figure 2 shows the typical notch characteristic with decibel as transmittance unit. The notch is positioned in a way that the notch minimum is at the reference wavelength and the notch width is per definition the distance between the transmittance maxima around the blocking range from λ_3 to λ_4. Only in such a diagram the blocking range around the notch minimum from λ_5 to λ_6 can be characterized directly. Figure 2 shows also the principle correlation between notch width and notch depth and gives a hint on the notch problem: The broader the blocking range the broader also the notch width or the deeper the notch depth, respectively. This interdependency of notch width and notch depth has to be considered during the design of a NF to check the required layer number and overall thickness, respectively. The next section gives a description how the effort can be estimated that is necessary to realize defined notch parameters.

2.2 Design approach

This novel view on the notch characteristic gives particularly the possibility to distinguish the requirements on pass band and on stop band because pass band smoothing does not influence remarkably the performance of the stop band or the notch characteristic, respectively. In this sense, we use the stop band characteristic of a standard thin-film optical filter with equivalent layers as a first design approach to estimate the design parameters of a required notch filter. After this, the refractive indices of the design approach are replaced by equivalent layers consisting in this case of H/L materials of a known deposition technology. Finally, smoothing the pass band or performing an apodisation will be the result of thickness optimization with an optimization procedure of any thin-film software.

We use the matrix formalism and the theory of equivalent layers to simulate the performance of a spectral notch [1, 2]. Without loss of generality we assume a symmetrical tri-layer of two materials A and B, periodically arranged onto a substrate, and normal incidence of radiation inside an ambient medium. The design of such a multilayer can be given by

$$\text{sub} \,/\, (A/2\ B\ A/2)^{S} \,/\, \text{air} \tag{1}$$

where sub and air stand for the substrate and the ambient medium, A and B stand for layers of materials A and B with quarter-wave optical thicknesses, s is the number of periods, and the corresponding refractive indices are n_S, n_0, n_A and n_B, respectively.

The tri-layer (A/2 B A/2) is represented by an equivalent index or the Herpin index and an equivalent phase thickness. Then, the complete multilayer with s periods of the tri-layer has the same Herpin index as the tri-layer and its phase thickness is s times the phase thickness of the tri-layer. Such a multilayer shows a lot of ripples within the pass band which has to be reduced if the multilayer stands for a notch filter. But this design requirement can be completely separated from the requirement on the stop band characteristic.

As mentioned above, the notch width is defined by the difference of wavelengths where the transmittance reaches their first maxima outside of the stop band. At such a transmittance maximum, the total thickness of the multilayer is a whole number of quarter-waves, that is, the total equivalent phase thickness of the multilayer must be an even number of $\pi/2$. If there are s periods in the multilayer, then the equivalent phase thickness will be s times the equivalent phase thickness of the tri-layer. At the edge of the pass band or the beginning of the stop band, the equivalent phase thickness is equal to π

and the first maximum of transmittance next to the stop band is then given by the period number s-1. Then, the notch width NW as a relative quantity in relation to a reference wavelength can be derived from the known formula for the equivalent phase thickness to

$$NW = \frac{4}{\pi}\sin^{-1}\left(\frac{(\rho^2 + 2\rho\cos\gamma + 1)^{\frac{1}{2}}}{1+\rho}\right) \quad (2)$$

with

$$\gamma = \left(\frac{s-1}{s}\right)\pi \qquad \text{and} \qquad \rho = \frac{n_B}{n_A}. \quad (3)\ (4)$$

As expected, the notch width acc. equations (2) to (4) becomes the known formula for the bandwidth $2\Delta g$ of a stop band using a quarter-wave multilayer of materials with refractive indices n_A and n_B,

$$2\Delta g = \frac{4}{\pi}\sin^{-1}\left(\frac{n_B - n_A}{n_B + n_A}\right)$$

if the period number s tends to infinity [2].

To derive the notch depth, we use the formula for the transmittance in the minimum of a stop band at the reference wavelength λ_0 on the assumption that $n_B > n_A$ and $(n_B/n_A)^{2s} >> (n_A/n_B)^{2s}$. The notch depth ND is then

$$ND = T(\lambda_0) = C\rho^{-2s} \quad (5)$$

or, using the optical density OD = -log (T)

$$OD_{ND} = 2s\log(\rho) - \log(C) \quad (6)$$

with a constant C given by

$$C = \frac{16 n_0 n_S}{(n_0 + n_S)^2 + (n_0 n_S/n_B - n_A)^2} \quad (7)$$

In this form, width and depth of a notch depend only on the ratio of the used refractive indices and the number of the periods. So, Eqs. (2) to (7) can be used to estimate the required refractive index ratio and the number of periods of the equivalent layer for a required notch filter.

Figure 3 shows an example of such estimation for the notch characteristic exclusively. The parameters of the required notch filter shall be a blocking range from 527 nm to 537nm around the reference wavelength of 532, a blocking depth of > OD5 and a notch width not greater than 24 nm. Using Eqs. (2) to (7), a relative notch width of 0.045 can be reached by a refractive index ratio of about 1.072, with a period number of 106 for a blocking > OD5. The index ratio 1.072 can be realized in two different ways: On the one hand, the lower refractive index is set to the index of silica with $n_A = n_L = 1.46$, which gives for the higher index a value of $n_B = 1.565$. This unsuitable refractive index can be substituted by an equivalent layer or a Herpin index using, for example, silica and tantala with $n_{H1} = 2.16$ at 532 nm. The H/L-stack acc. Eq. (1) has an overall physical thickness of 18.9µm with a design given in physical thickness by

$$\text{sub}\ (85.67L\ 6.82H1\ 85.67L)^{106}.$$

On the other hand, the higher refractive index is set to the index of niobia with $n_B = n_{H2} = 2.36$, which gives for the lower index a value of $n_A = 2.202$. This can be seen as an unsuitable refractive index that can be substituted by an equivalent layer or a Herpin index using, for example, niobia and silica. The H/L-stack acc. Eq. (1) has an overall physical thickness of 12.2µm with a design given in physical thickness by

$$\text{sub}\ (53.57H2\ 8.09L\ 53.57H2)^{106}.$$

The two methods differ in the overall thicknesses and the material for the very thin layers. These differences can be used to choose the suitable deposition technology or the monitoring method. Two real examples of such SNF are shown later in the results.

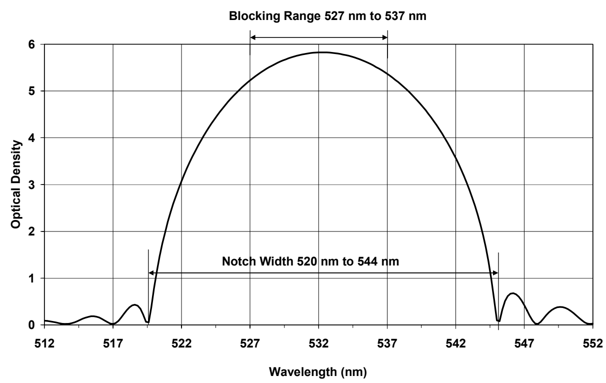

Figure 3: Notch filter characteristic with ρ=1.072 and s=106.

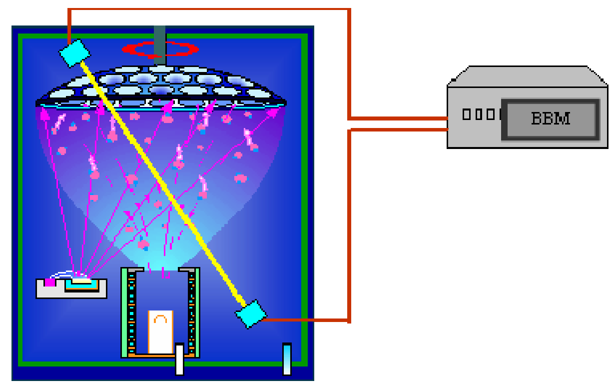

Figure 4: Schematic diagram of a PIAD process with intermittent monitoring on dome (right).

2.3 Manufacturing methods

2.3.1 PIAD

With SNF we demonstrate the feasibilities of plasma-IAD using a SyrusPro box coater with APS technology [3] and a broadband monitoring system (BBM) [4] to control the multilayer stack. The box coater schematically shown in Figure 4 is equipped with electron beam evaporators, type HPE 10, a 1050 mm diameter dome shaped substrate holder with single rotation and the advanced plasma source (APS). The optical thickness control of the multilayer stack is done directly on the dome in an intermittent measurement mode on a monitoring glass. The control electronics of the BBM is synchronized with the substrate drive. At each rotation the transmittance is measured for a few milliseconds while the monitor glass is crossing two fiber collimators. More details about the features and the capabilities of the BBM were described in reference [4]. The typical deposition rate of PIAD is 0.5nm/s for the whole dome.

2.3.2 PARMS

The most challenging SNF and MNF filters were demonstrated with magnetron sputtering and monochromatic optical monitoring. Figure 5 shows an overview of our HELIOS magnetron sputtering tool, Figures 6 and 7 show details of the PARMS technology with monochromatic intermittent monitoring [5, 6]. Substrates respectively substrate carriers are loaded via a load lock on to the substrate turn table. The customized turn table layout has a useful substrate area of approx. 1200cm². The standard sputtering module is equipped with 2 MF dual-magnetrons, 1 RF plasma-source and 1 in-situ optical monitoring system (OMS 5000). Main features of the innovative sputtering solution are a fully automated, real clean-room compatible deposition process, a high turn table rotation speed >200rpm, stable reactive sputtering free of any arcing, a lowest defect level, a high deposition rate and rate stability, direct on substrate optical thickness control, high production yield and throughput. The principle of PARMS technology is the combination of dynamic reactive MF magnetron sputtering with partial pressure control and a reactive assist process with the RF plasma-source. Per rotation thin sub-stoichiometric oxide layers are deposited and transferred to non-absorbing oxide layers by the reactive assist process. Depending on the filter design the multilayer stack is controlled by OMS, by time or combinations of both on one or multiple monitoring substrates. For the notch filter manufacturing we used a fully automated combination of OMS- and time control.

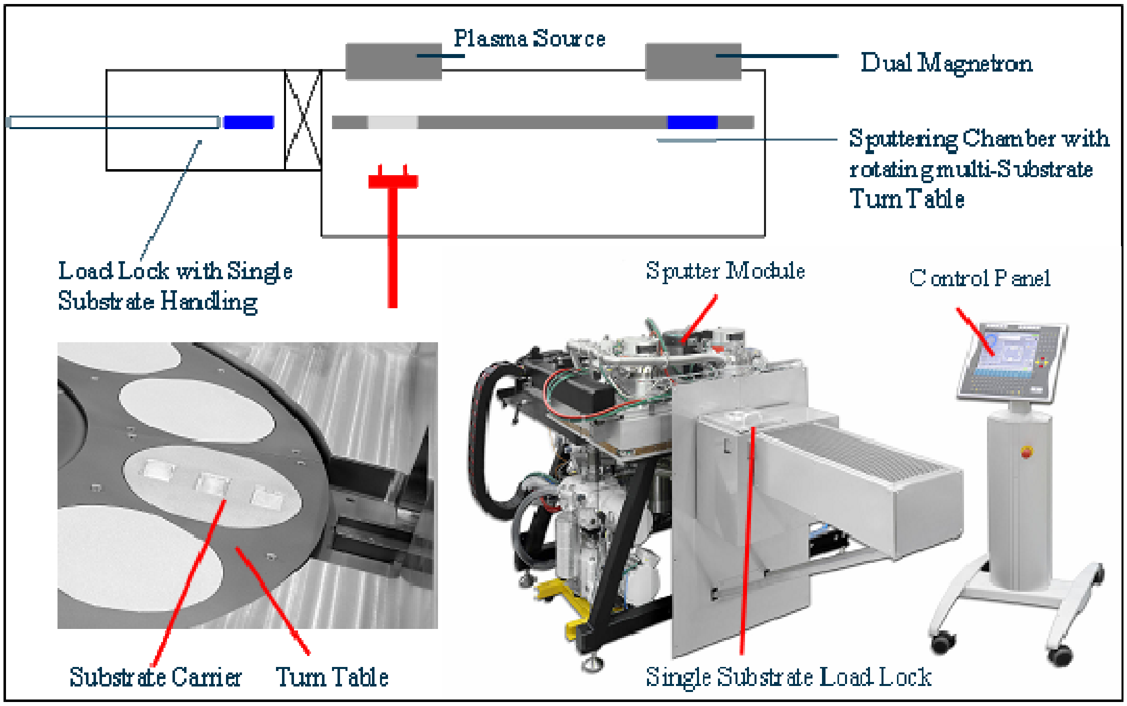

Figure 5: Overview of HELIOS magnetron sputtering tool with PARMS technology

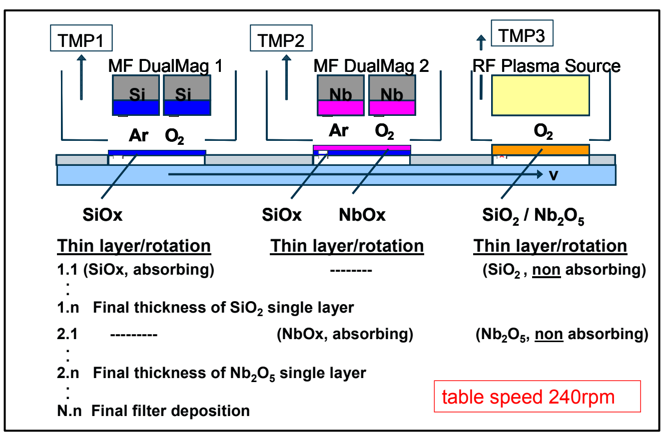

Figure 6: Details of PARMS technology

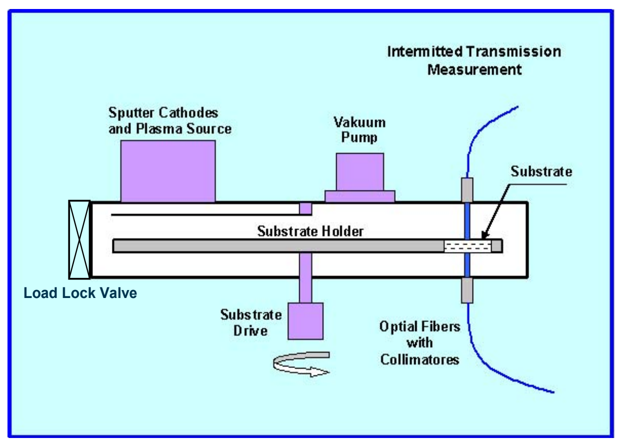

Figure 7: Single wavelength intermittent monitoring

3. NOTCH FILTER RESULTS

3.1 SNF by PIAD

The basic single notch filter characteristic of Figure 3 was used as a real example for the reference wavelength of 532nm. The final design optimization led to a multilayer with 185 layers and an overall physical thickness of 17.4µm by using silica and tantala. In this approach most of the tantala layers are very thin down to 5nm while most of the silica layers are very thick. The result of such a notch filter is shown in Figure 8 produced by PIAD with a Leybold Optics SyrusPro. Due to the fact that challenging notch filters are difficult to manufacture with a reasonable yield with evaporation processes even with PIAD we investigated the potential of our advanced magnetron sputtering process.

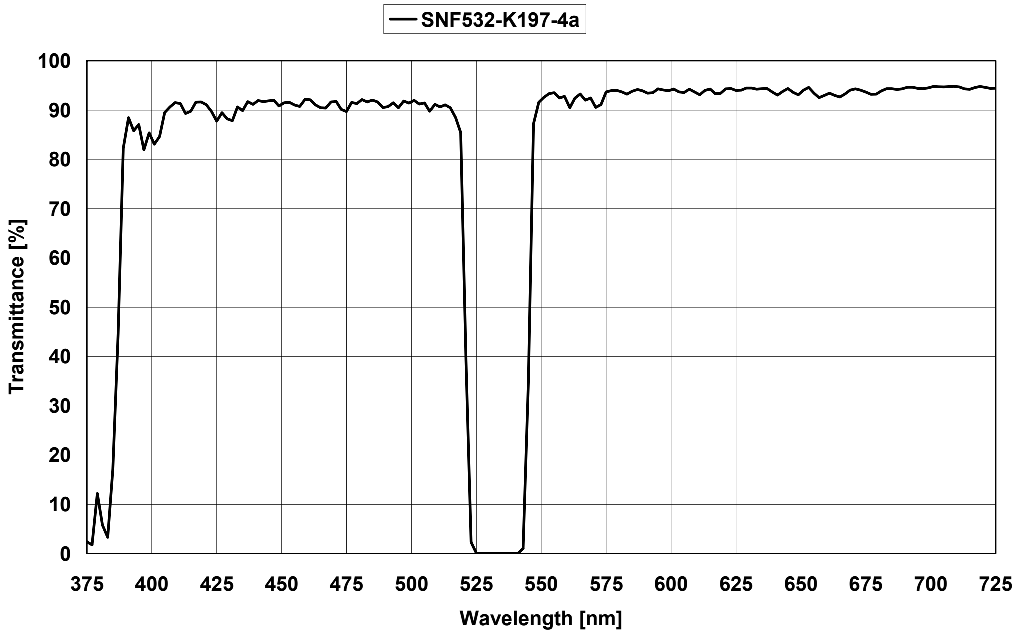

Figure 8: Measured spectral notch filter performance, SNF532OD5

3.2 SNF and MNF produced by PARMS

We have optimized different notch filter designs for the visible spectrum, single notch filter and multi notch filter. We used in both cases silica and niobia as low index respectively high index material. The optimized designs are based this time on thick high index layer and thin low index layer.

At first we designed again a single notch filter with a reference wavelength at 532nm, in this case with a notch width of 16nm and a blocking range of 6nm with an optical density OD > 3.5. The specified average transmittance in the pass band specified between 400 and 520nm respectively 545 and 700nm was > 85%. The design led to a multilayer with 140 layers and a total physical thickness of app. 15µm. The total thickness of silica was < 1µm with a main thickness range between 3 and 12nm. The total process time including substrate handling was < 11hour.

Figures 9 and 10 show the transmittance of such notch filter produced with our HELIOS in comparison with the theory calculated without absorption and with absorption based on measurements of single layers and the run to run reproducibility. Figure 11 shows the transmittance in dB and the OD at the notch. The average transmittance in the pass band is far above the specified value of 85% and corresponds very well with the theoretical value of 95% with outstanding low ripples in the whole spectrum. Due to the absorption of the niobia layers the transmittance starts to decrease below 450nm. The notch width is with 17nm slightly larger than the design value of 16nm. The run to run reproducibility measured at the notch is < 0.4nm or < 0.1%. The maximum optical density shown in Figure 11 is OD > 4 and the blocking width for OD > 3.5 is with 8nm higher than the design value of 6nm.

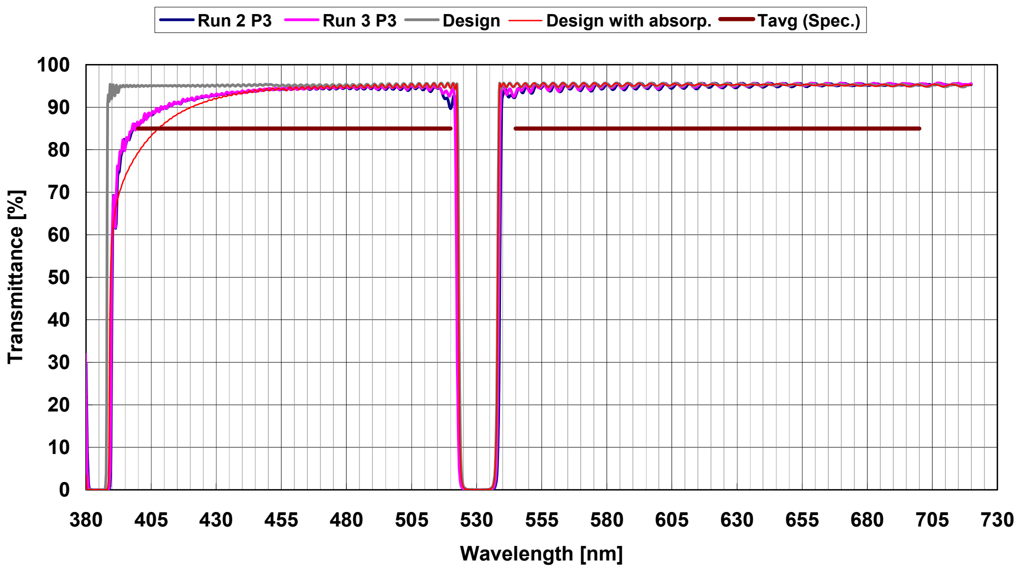

Figure 9: Spectral transmittance of SNF for 532nm with OD > 4. Comparison with theory and run to run reproducibility.

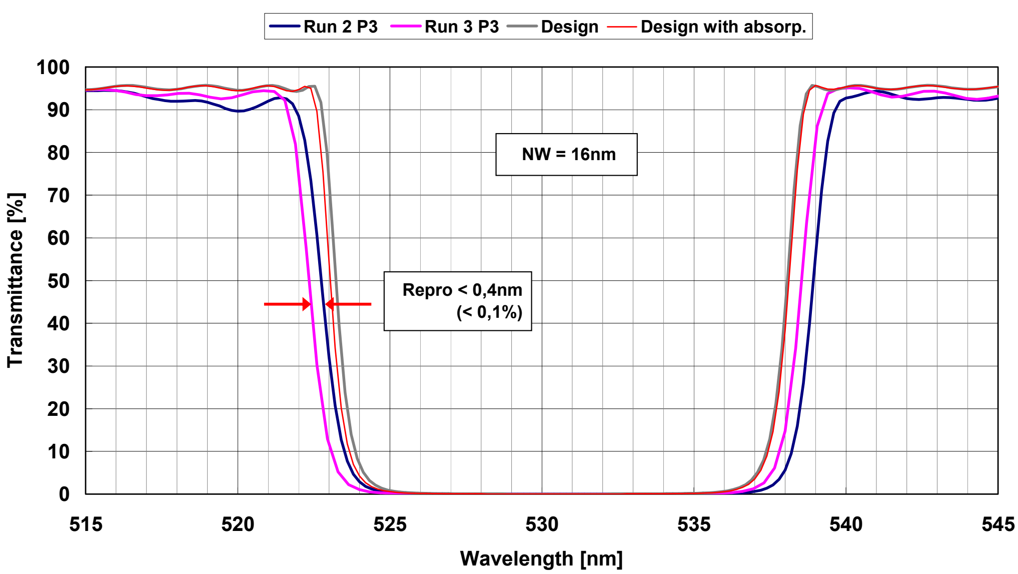

Figure 10: Details of the blocking range

Figure 12 shows the uniformity within one run measured on 10 positions of the turn table. Due to the high speed of the turn table the uniformity within one run is extremely good and in this case < 0.2%. The measured deviation is therefore mainly given by the mechanical tolerances of the turn table positions that mean deviations between the distances from the individual substrate positions to the sputtering targets. With a new designed water cooled turn table this deviation can be controlled within ± 0.1mm which correlates to a thickness deviation of 0.1%.

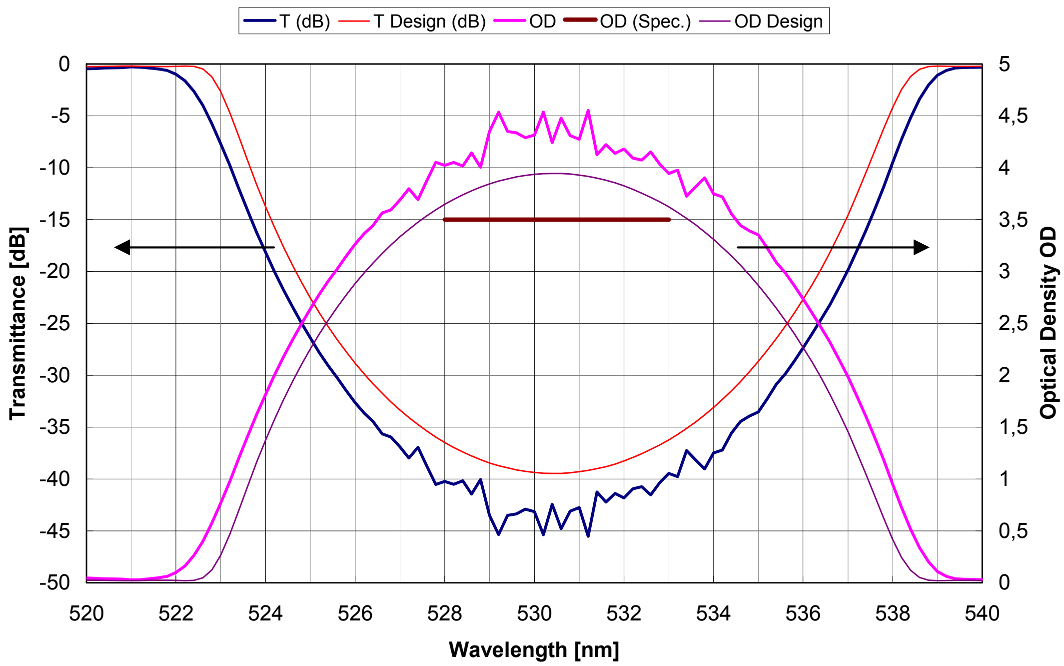

Figure 11: Transmittance in dB and optical density OD of the blocking range

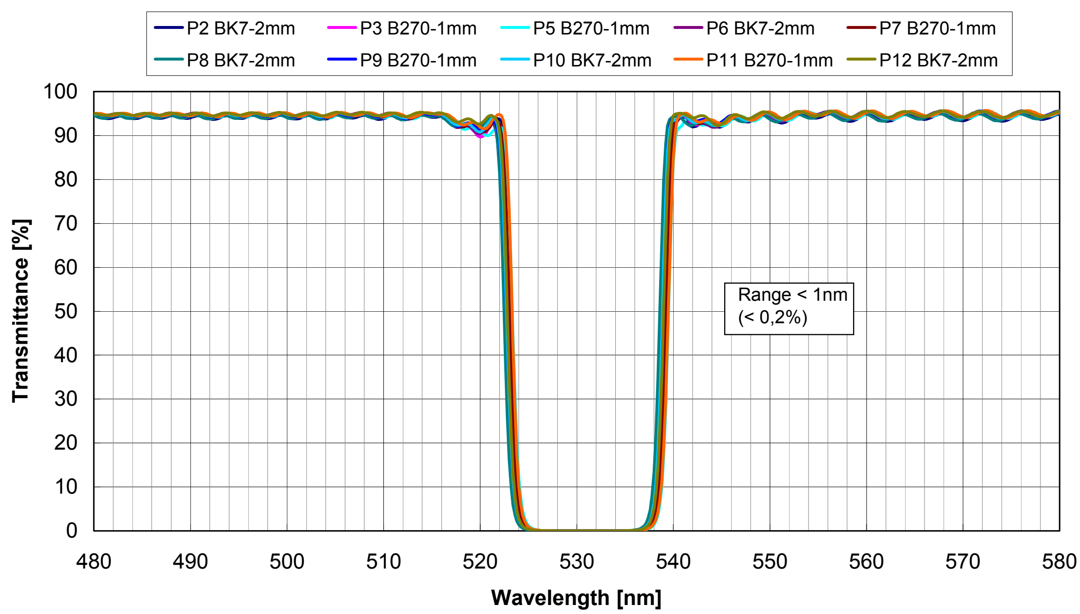

Figure 12: Uniformity within one Run measured on 10 substrate carrier position of the turn table

The high degree of coincidence between experiment and theory and the run to run reproducibility is due to the very stable dispersion and deposition rate of our reactive sputtering process in combination with the high accuracy of the monochromatic optical monitoring [7]. This allows a fully automated combination of layers controlled by optical monitoring and by time whereas the time controlled process is in situ calibrated by the optical monitoring.

As a most challenging design to demonstrate the capability of our sputtering tool we used a quadruple multi notch filter with following specification (with backside reflection):

- Pass band: T avg. > 86% @ 458 – 476, 500 – 542, 568 – 622, 654 – 750nm; T min. > 66%
- Blocking range: R > 90% @ 440 – 449, 486 – 490, 553 – 557, 635 – 641nm; OD > 4

The design of such a multi notch filter cannot be directly derived from the theory of a single notch filter. But with the optimization procedure of thin-film design software the same basic solution as for single notch filter is obtained.

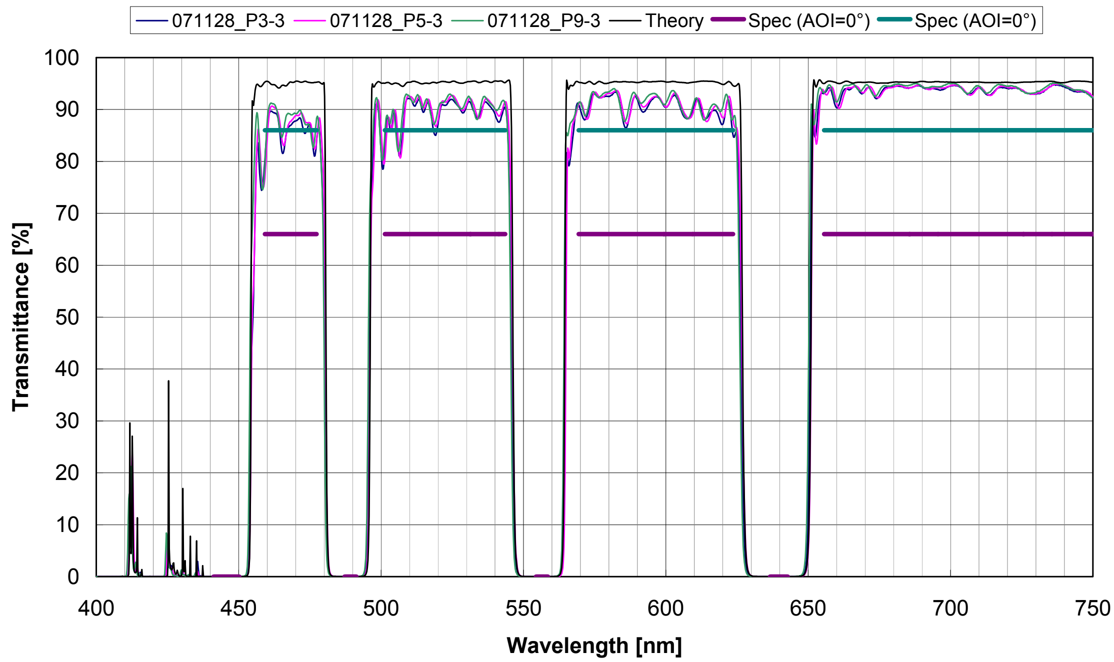

Figure 13: Spectral performance in transmittance of a quadruple multi notch filter based on Nb_2O_5 / SiO_2 for AOI 0°.

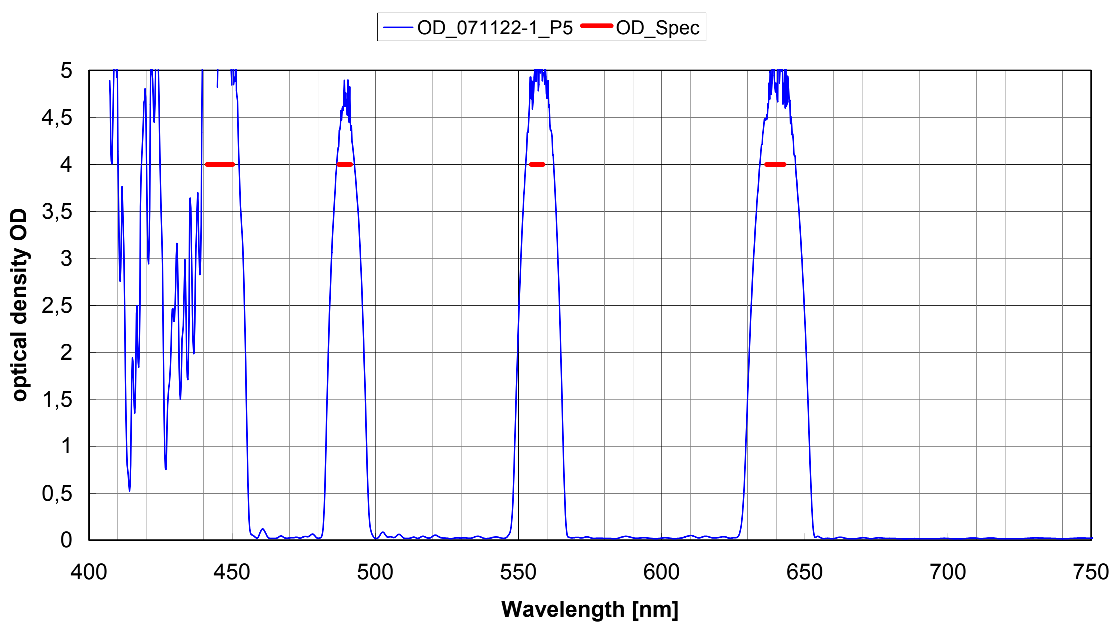

Figure 14: Comparison of measured and specified optical density OD of the quadruple multi notch filter for AOI 0°.

We used again silica and niobia as low and high index layers. An optimal design is based on 198 layers with a total thickness of approx. 20µm whereas niobia and silica is 16.8µm respectively 3.1µm thick with silica thicknesses as low as 4nm. The total process time including substrate handling is < 14h. We used the same control strategy as for the single notch filter. Figure 13 shows a comparison of the measured spectral transmittance with the theory for an AOI of 0° and backside reflection. The average and minimum transmittance of all 4 pass bands is far above the specified value of 86% respectively 66%. The ripple is not as low as in the case of the single notch filter but relatively low for this challenging filter characteristic and we have to notice that this result is obtained with the first run. The uniformity within one run as well as the run to run uniformity is as low as in the case of the single notch filter.

Figure 14 shows the comparison of measured and specified optical density (OD). In all for notch or reflectance bands the blocking range of OD > 4 is higher than the specified values.

4. CONCLUSIONS

In this paper we demonstrated the experimental realization of challenging notch filter characteristics based on a approach of replacing the second refractive index by equivalent layers consisting of H/L materials with high index contrast. This leads to a minimum multilayer stack thickness with a combination of very thick and very thin layers. To estimate the effort for manufacturing a notch filter, firstly, we defined the parameters notch width and notch depth to characterize an notch filter in a novel manner, and secondly, we derived two formulas from the theory of equivalent layers to calculate these parameters in dependence of the refractive index ratio of the used materials and the number of periods required for the multilayer. With plasma-IAD (PIAD) using a SyrusPro box coater with APS technology such single notch filters could be manufactured but with limited yield. Most challenging single and multi notch filter could be effectively manufactured with high yield and reproducibility with plasma assisted reactive magnetron sputtering (PARMS) and monochromatic optical monitoring in our HELIOS sputtering tool. As examples we used a single notch filter for 532nm and a quadruple multi notch filter for the visible spectrum. Due to both, a high deposition rate and a high useful substrate area, the manufacturing costs with our HELIOS tool are low compared to other techniques like ion beam sputtering (IBS) which is mainly used so far.

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