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Design and Realization of multispectral Bandpass Filters for Space Applications

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ABSTRACT

Spectral and radiometric requirements of optical filters for space applications are always more demanding. Multispectral bandpass filters require very steep edges, a high accuracy in the central wavelength position, a high average transmittance as well as a very good level of blocking outside of the bandpass region.

Realization of such filters implies to design the layer stacks in a way that reduces sensitivity to the production deviations and to be able to properly control the coating conditions in the machine.

In order to optimize the design, a pre-production error analysis can be performed, to assess the weight of each layer in the global filter properties and therefore modify the design until a good stability level is achieved. We discuss different insitu optical monitoring strategies and process conditions depending on the coating technology. The realization phase needs a precise control of the coating machine such as well-characterized deposited materials, stable deposition rates, a reliable layer thickness monitoring system in addition to a good coating uniformity over all the coating positions inside the machine.

We present design strategies and means of pre-production error analysis for typical multispectral bandpass specifications as well as transmittance curves.

Keywords: optical filter, multispectral, bandpass filter, interference filters, filter assembly, spaceborn instrumentation

1. INTRODUCTION

Multispectral imaging is used in satellite applications and air reconnaissance operating with optical filters that cover at least the typical red, green and blue channels and a near infrared channel to produce 2D images. Some applications use even more channels. The incident light spectrum is measured and the spectral bands determined by the filters have to be continuous. Therefore the transition between the different color channels has to be steep and well defined. The crosstalk between the channels has to be suppressed by a patterned black chrome mask which is well aligned on the light incidence side and the exit side. Thereby a staircase of different center wavelengths are produced in one direction (stepped filters) that produce a 2D mosaic, which are suited for the snapshot technique. Due to the increasing requirements of multispectral imaging the specifications of the bandpass filters being one of their key elements tend to be more and more demanding as well. For this reason a preproduction study of process variations is of growing importance. Such simulations can for example take the layer design of the interference filter stack and process parameters into account which can influence the deviations between theoretical and practical performance of the filter transmission spectrum in terms of centerwavelength, full width at half maximum (FWHM) or passband ripple. Furthermore an estimation for a spectral uniformity on the coated area of the filter surface can be done. The simulations yield crucial information about for example critical layers, thickness error accumulation, critical wavelength ranges of the filter performance, requirements for the insitu optical monitoring system or the required effort for layer thickness uniformity.

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As a consequence a layer design with optimized rigidity in the coating process can be chosen and key parameters of an optical process monitor can be adapted or it can be decided, if a filter would be better controlled by monochromatic or broadband optical monitoring.

The best choice to deposit durable and environmental resistant optical filters with temperature stabile spectral characteristics are ion based processes like ion assisted deposition (IAD), magnetron sputtering (MS) [1] or ion beam sputtering (IBS). Those processes yield highly dense coatings with strong compressive stress, so in most cases it is necessary to account for this stress by either distributing the filter coatings on both sides of the substrate or by depositing a suitable thickness of SiO_2 and an antireflection (AR) coating on the backside. To estimate the thickness of a SiO_2 compensation layer, a common approach is to take the sum of all SiO_2-layers of the filter stack and multiply it by a factor 1.1 to 1.4 (depending on deposition technology). This will give a good basis for a rough assessment of the needed compensation thickness, which can be fine-tuned further by several coating runs. It is also possible to do a more elaborate estimation by statistical evaluation of parameters like number of layers, overall thickness ratio of the layer materials, total coating thickness, elastic modulus of the substrate and the ratio of surface to thickness of the substrate into account.

There are 2 principal choices of design of an array of multispectral bandpassfilters. First and widely used in the industry is the deposition of bandpass filters on individual lithographically masked substrates and subsequent glueing of diced strips of different filter types side by side on a base substrate or a filter frame. The individual filter channels are masked on the entrance and exit side with a microlithographically masked black chrome coating which reduces the internal reflections inside the substrate to avoid ghost images. This black chrome coating can also be designed to reduce the internal and external reflections for the case when an AR-coating is applied instead of a filter coating (e.g. on the exit face). Secondly the different filter types covering different bandpass ranges can be deposited successively on the same substrate with a lithographic mask covering all channels but the one where to coat the current filter. Of course the second approach is much more yield driven, as a defect in masking or coating of only one of the filters leads to rejection of the whole filter array. We present results of arrays of filter strips done with the first approach.

2. COATING DESIGN APPROACHES

The coating designer can choose from 2 basic principles for basic interference filter designs: For narrow bandpass filters with a FWHM below approximately 5% of the central wavelength a Fabry-Perot design, composed of mirror layers and resonator layers is mostly a good choice. It requires additional layers to achieve a good blocking in a wider range (e.g UV to NIR). The advantage of a Fabry-Perot design is, that its centerwavelength and FWHM is well defined by design and stabil in production [2]. For larger filter widths and broad blocking range a design with multiple dielectric quarter wave stacks is a better choice. In Fig. 1 an example of a narrow bandpass with Fabry-Perot design is shown without additional blocking layers which would be designed equal to a large bandpass filter and deposited on the backside or on top of the Fabry-Perot layer stack. In Fig. 2 a broadband NIR-bandpass design is shown based on a multiple quarterwave mirror design with 4 displaced mirror stacks is shown. Each mirror stack has about 24-32 layers which adds up to about 100 layers. The necessary number of mirror stacks depends on the width of the blocking region. To widen the range, more stacks have to be added. The number of layers within one stack determines the level of blocking of each of the stacks. To optimize the spectral performance to steep spectral transitions and high transmission with minimized oscillations, different mathematical optimization algorithms can be used that vary the thickness of the chosen layers. The coating designer therefore chooses appropriate target values in the transmission range and blocking range. Preferentially one would take care, that very thin layers or very thick layers are avoided. In modern design programs there are algorithms that take the sensitivity of small thickness variations into account and can optimize the layer thicknesses to achieve a design which is robust in production [3]. It is also advantageous to set a minimum thickness limit already in the course of the optimization (e.g. the thickness should not be lower than 15-20 nm). Especially for multispectral filters it is a good strategy to choose a starting design for optimization, that has enough stacks and enough individual layers in the stack to conveniently achieve a good blocking already before the start of the optimization in order to leave enough degrees of freedom for the optimization. By this approach the optimization can give up a bit on the blocking performance to achieve a very high and smooth transmission range with steep transition regions without altering the individual thicknesses too much. Very thin (<15nm) and very thick layers (several hundreds of nm) which might cause problems in production can therefore be better avoided. However an excess of layers will be at the expense of coating time and complicates the design, so care must be taken to find a good compromise. As a rule of thumb, the average blocking of the starting design should be about one order of magnitude better than the optimization targets. Generally, it is advantageous to find a design, where the initial structure of the quarterwave stacks is as well conserved as possible, because the optical process monitoring will show a high and consistent amplitude in each layer. This in turn leads to good stop conditions of the deposition of the layers, controlled by the optical process monitor device measuring transmission or reflection through the growing film. Good stop conditions will lead to a stabile process and a good match between theory and measured performance. Most of the variations of layer thicknesses from the starting design occur at the end of the layer system (antireflection to incident medium) and at the beginning (matching to substrate index). Therefore, a good approach is to do a first optimization with a slow algorithm on all the layers, which keeps the structure of the quarterwave stacks, in order not to change the individual thicknesses too much. Then, the innermost and outermost layers can be optimized separately with a more intrusive algorithm. Sometimes the layers adjacent to the neighboring quarterwave stacks should also be included in more insistent optimization, but with some caution with respect to the points mentioned before. At the end of a design optimization procedure it is always a good idea to eliminate very thin and very thick layers and check the sensitivity of the remaining thin layers.

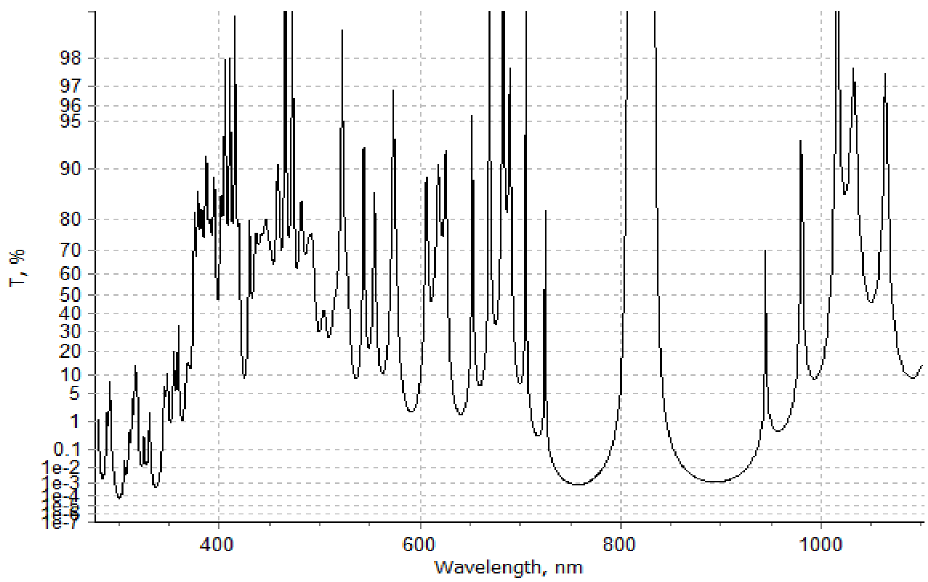

Fig. 1 Fabry-Perot filter design with 40 layers and 5 cavities and a FWHM of 35nm. To achieve a broad blocking one would have to add 60-80 layers.

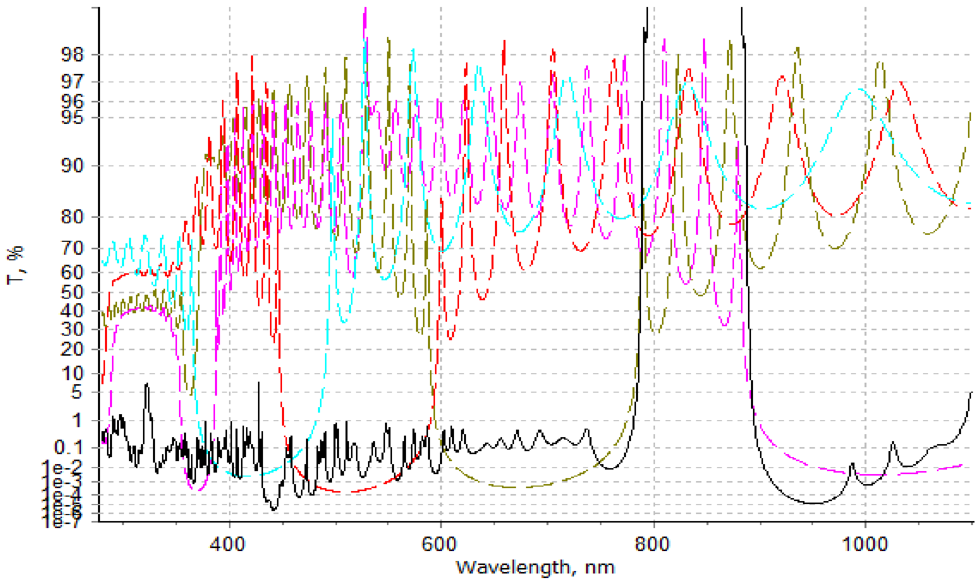

Fig. 2 Broadband filter design based on 4 differently centered quarterwave mirror stacks with about 100 layers. The individual mirror stacks are displayed in discontinued curves and different colors. The optimized final design is the black continuous curve.

3. SIMULATION OF PROCESS VARIATIONS

The design can of course be directly programmed on the machine and a test run could be done. But as coating time is costing time and money, it is preferred to do some simulations upfront: Once one or several designs have been made, one should filter out the most stabile candidate for further simulations. This can be done in a first simple step by a simple error analysis, introducing a common absolute and relative rms thickness error for all the layers and run a sequence of 500 tests with a statistically distributed error. Figure 3 shows this error analysis for two candidate designs. Based on this fast test, one would choose the design on the right hand side in Figure 3.

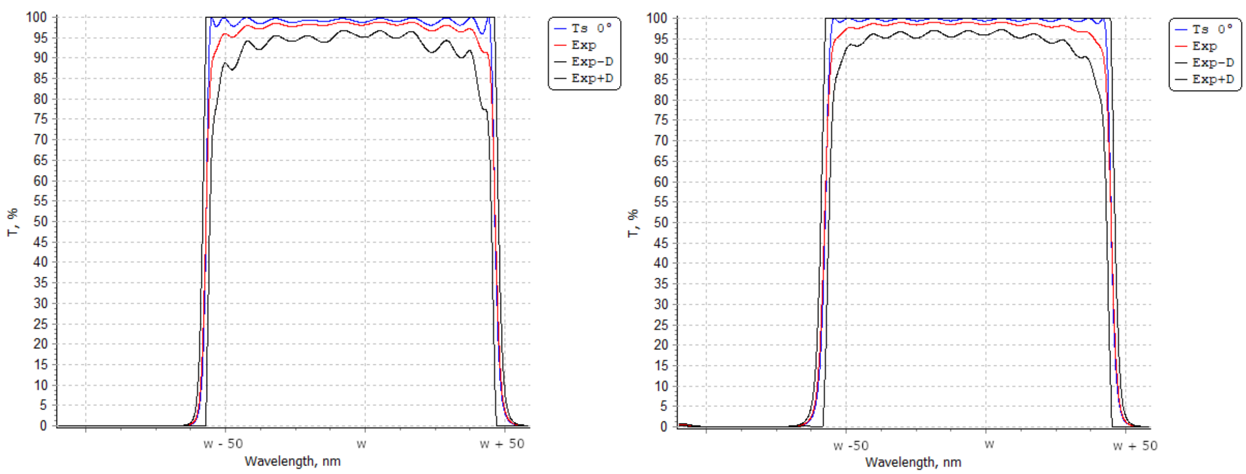

Fig. 3: error analysis for two candidate designs. The blue curve is the theoretical design, the red curve is the statistically expected mean curve, the lower and the upper black curves determine the tolerance channel for a preset probability corridor of 95%. Based on this fast test one would choose the design on the right hand side.

In the next step, the process control strategy is setup. This can be done by monochromatic monitoring measuring the evolution of the transmission/reflection signal during the growth of every layer with a monochromatic probe beam or broadband monitoring measuring the transmission/reflection spectrum typically between 400nm and 1000nm [4]. In the monitoring strategy, the suitable monochromatic wavelengths or broadband ranges are determined as a function of the layers and a possible change of test glasses are planned. It can also be chosen, whether a layer controlled by time/power or rotation speed instead of optically. Subsequently the deposition process can be simulated in a software [5], that takes the key parameters of the coating plant, the optical process monitor and known typical variations of the deposition process and coating materials into account. Those parameters are for example: rotation speed of the substrates, deposition rate (nm/s), shutter delays, measurement time and frequency, spectral resolution, noise, integration time and typical variations of deposition rate and refractive index. The simulation result are absolute or relative errors for every layer and a simulated transmission spectrum that shows the deviation between simulation and theory. If the result is deviating too much from the theoretical spectrum, the monitoring strategy should be adapted. For example if excessive errors in certain layers or an accumulation of thickness errors is visible, an additional change of a test glass can be introduced, a layer can be determined by time or rotations or in the case of monochromatic monitoring also a different wavelength, resolution or integration time can be chosen. If the result is coinciding reasonably well with the theoretical transmission curve, the table of simulated errors can now be used for a statistical test. So the errors determined in the process simulator can be used for another sequence of 500 tests with the individual layer errors set as rms-errors. This yields an indication if a more realistic error distribution, based on simulated process conditions, would also yield a good result fulfilling the spectral specifications.

The set of 500 tests can then be evaluated for the spectral characteristics of each test, for example for average transmission, centering, FWHM, left and right flank and the yield probability can be evaluated at a 3σ-level for example. Figure 4 shows the results of this evaluation. One can see the deviations for each of the spectral characteristics and compare with the tolerances given for the filter.

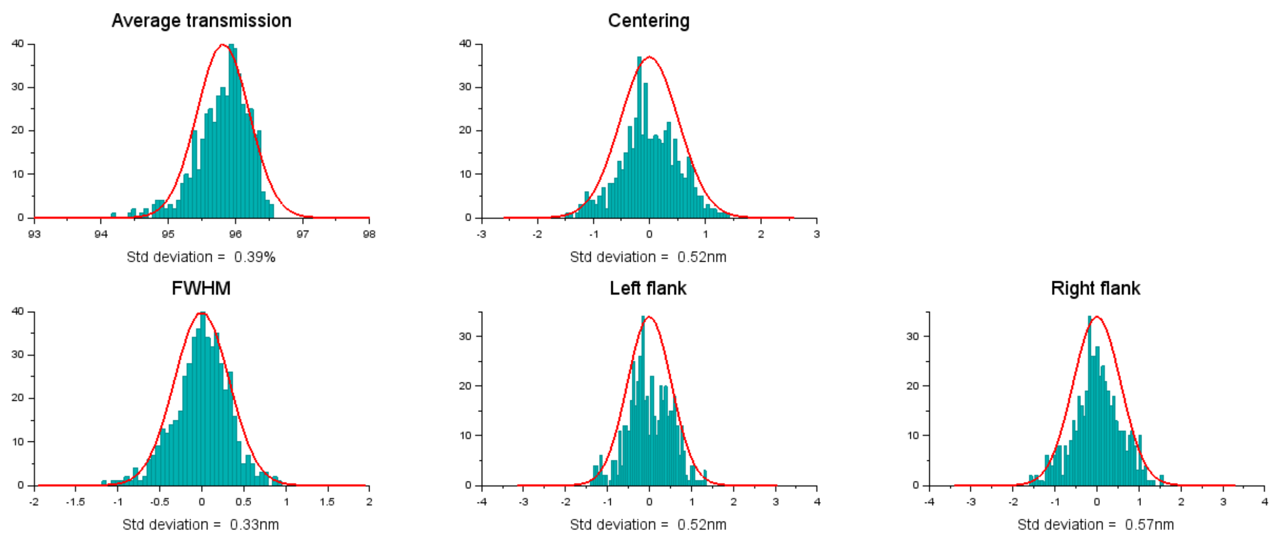

Figure 4 shows the results of the evaluation of the spectral characteristics of each of the 500 tests for average transmission, centering, FWHM, left flank and right flank. The Gaussian fits can then be evaluated for yield probability on a 3σ-level for example.

The result of the production of the theoretical design with a PARMS magnetron sputter process [1] can then be compared to the theoretical curve, the statistical envelope and the expected mean curve. Figure 5 shows the measured curve in blue (note that the backside is uncoated unlike the simulations above), the theoretical design curve in yellow, the statistically expected mean curve and the lower envelope of the 95% probability corridor. The thickness errors to create 500 simulated test runs where determined for each individual layer by a process simulation with realistic process conditions. One can see that the measured curve lies mostly above the mean expected curve and resembles nicely the theoretical design curve. This indicates that the variation of the process parameters fed into the process simulation tend to be slightly pessimistic compared to the mean expected curve.

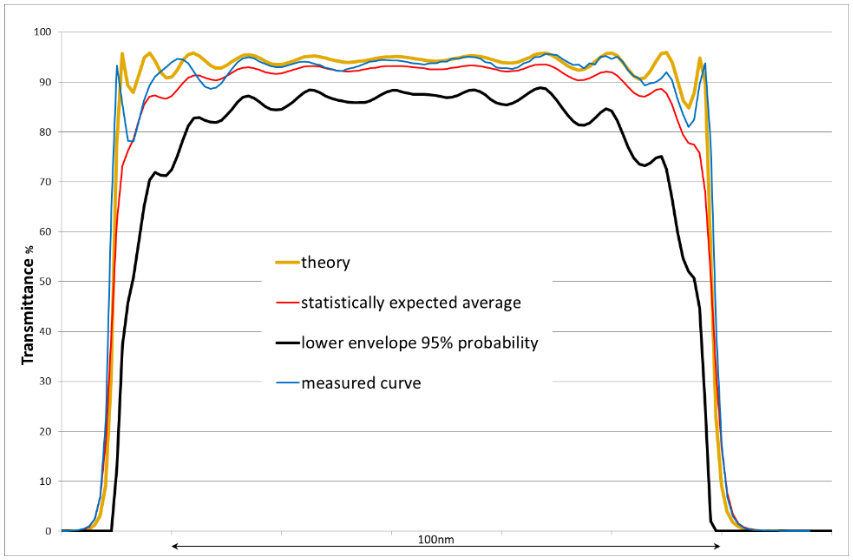

Fig. 5 shows the comparison of the measured curve of a magnetron sputtered filter (blue) with the theoretical design curve (yellow), the statistically expected mean curve (red) and lower envelope of the 95% probability corridor (black) of 500 simulated test runs.

The spectral uniformity over a wafer surface of magnetron sputtered filter was also evaluated and shows satisfying results with a maximal value of ±0.24% over a 105x120mm area where the sticks are located (Fig.6). On a black-chrome masked wafer the filter spectral uniformity along the length of the sticks was smaller than 0.2% (Fig.7).

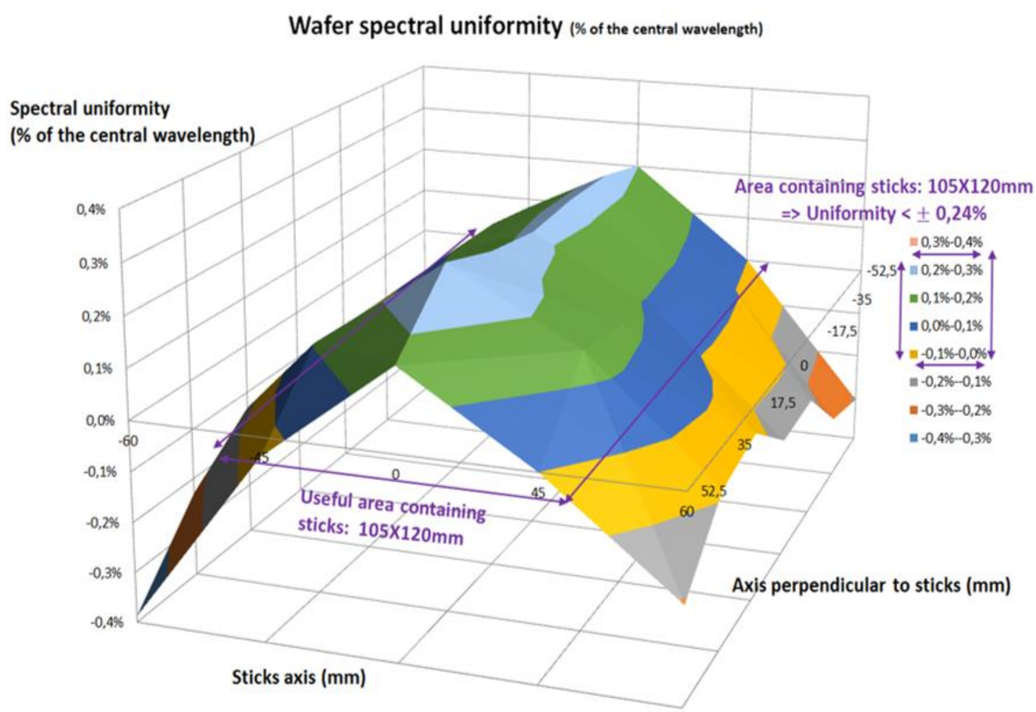

Fig. 6 shows the spectral uniformity of a magnetron sputtered filter in the useful area 105x120mm of a non-masked wafer. The uniformity is below +/- 0.24% over the surface where the sticks are located.

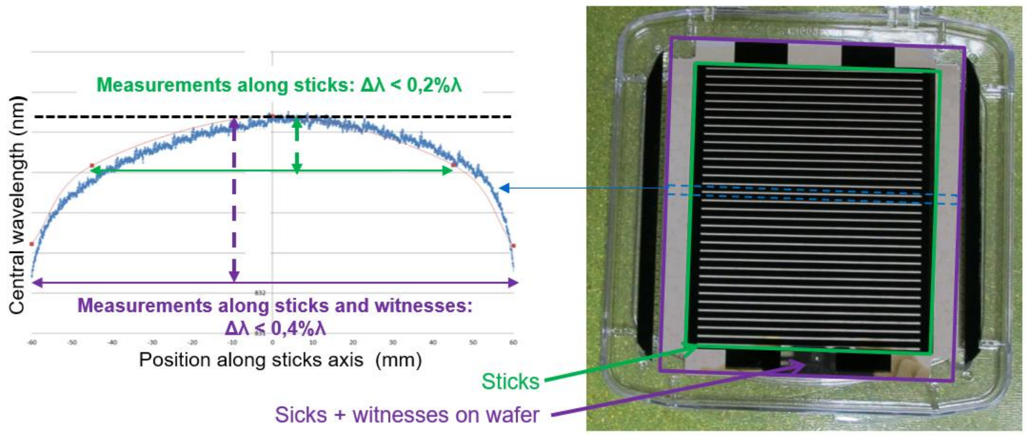

Fig. 7 shows the spectral uniformity along the sticks and witness areas an a black chrome masked wafer.

For a narrow bandpass filter with narrowband Fabry-Perrot designs even better uniformities could be achieved in the frame of an astronomy -Project, for which the spectral uniformity was reduced even below 0.1% on a 100x100mm area [6]. The reason for a better uniformity of a Fabry-Perot narrow bandpass filter is, that in this case the coupling of the longwave and highwave flancs is very intense by design, whereas the filter slopes grow steeper with each cavity. In the case of a broad bandpass as presented, the lower wavelength flanc is produced by one layerstack and the higher wavelength flanc by a different one with the individual layers in the stack having quite different thicknesses and different sensitivities to layer thickness errors. Thus contributing differently to the spectral uniformity of the whole spectral characteristics.

4. BLACK CHROME COATING

The black chrome coating is a multilayer coating consisting of chromium and dielectric layers to minimize the reflection on the internal glass side and minimize the transmission through the black chrome. The residual reflection can be adjusted to the desired wavelength range to values below 1% depending on the substrate material. Figure 6 shows the reflection spectrum of a black chrome coating adapted for the broadband filter which was discussed before. The transmission level of the black chrome depends a bit on the wavelength range and is in average between 0.01 and 0.1%. Figure 7 shows the transmission spectrum of the same black chrome layer system.

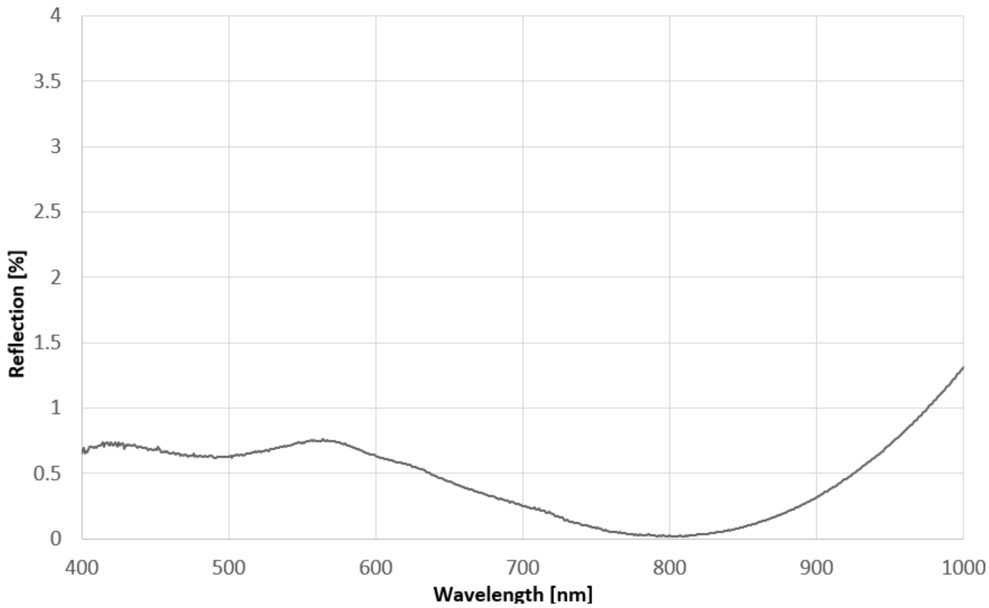

Figure 7: measured reflection spectrum of a black chrome coating adapted for the broadband filter discussed above.

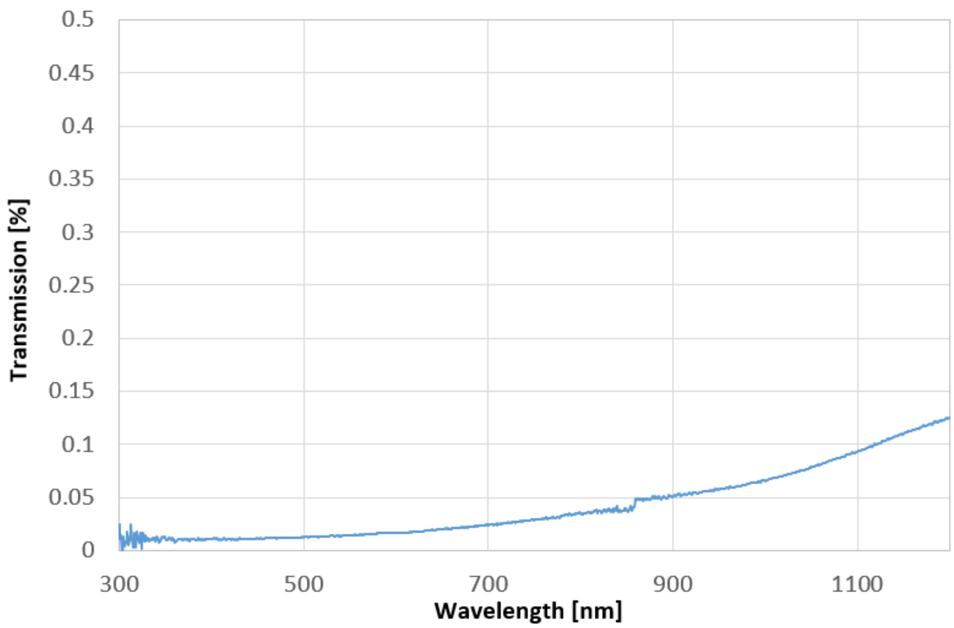

Figure 8: measured transmission spectrum of a black chrome coating adapted for the broadband filter discussed above.

5. CONCLUSION

The optimization of the production of a demanding bandpass filter was realized by taking care of different aspects: to find the most rigid design in production, by keeping as much as possible the structure of the stacks and to apply thickness optimizations that minimize the sensitivity to thickness errors, to perform a pre-production error analysis to determine where the sources of deviation lie in the production process, and simulation of the in-situ monitoring strategy. The evaluation of the simulation results with statistical methods allows to estimate a yield in the production process. The realized filter exhibits a profile very close to the theoretical curve, and the measured transmission curve lies above the statistically expected curve, showing that the process simulation reflects very well the real process.The whole process for coating, backside stress compensation, masking, dicing and assembly of multispectral filters was implemented for a magnetron sputtered filter. We prove the ability for high demanding performances with a deviation from theory to realization of +/- 1nm. The magnetron sputtered filters show a better match to theory especially with highly complex filters than filters produced with ion assisted deposition methods.

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