Design and manufacturing of high performance notch filters

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ABSTRACT

Rugate designs for the realization of notch filters are well known in the literature. The required deposition of gradient index layers is difficult to manufacture. In our approach we apply the equivalent index theory to replace the gradient index profile of a notch filter design. We produce single and multiple notch filters with plasma ion-assisted deposition and broad-band optical monitoring. As examples, a 500nm notch filter for the GREGOR telescope and a 589nm notch filter for the GALACSI instrument of the VLT are discussed. Additionally, a 4-line multiple notch filter and a 218nm notch filter made for fluorescence spectroscopy applications are presented.

Keywords: Notch filter, Dichroic, Ion-Assisted Deposition, Magnetron Sputtering

1 INTRODUCTION

Selection of a spectral band from a broad incoming spectrum is frequently task of an optical device for astronomical observations and remote sensing of the earth.[1,2] This task is mostly performed by thin-film optical filters that are applied as dichroics or as band-pass filters. They consist of multilayers of materials of different reflective indices and realise spectral characteristics defined by the dependence of transmission or reflection on the wavelength and the angle of incidence (AOI) of the incoming beam.[3] In any case, the spectral selection is connected with a geometrical splitting of the beam into a reflected beam and a transmitted beam. The GALACSI optics system as part of the Adaptive Optics Facility (AOF) of ESO's Very Large Telescope (VLT) shall be an example of such a spectral selection and geometrical splitting system (Figure 1).

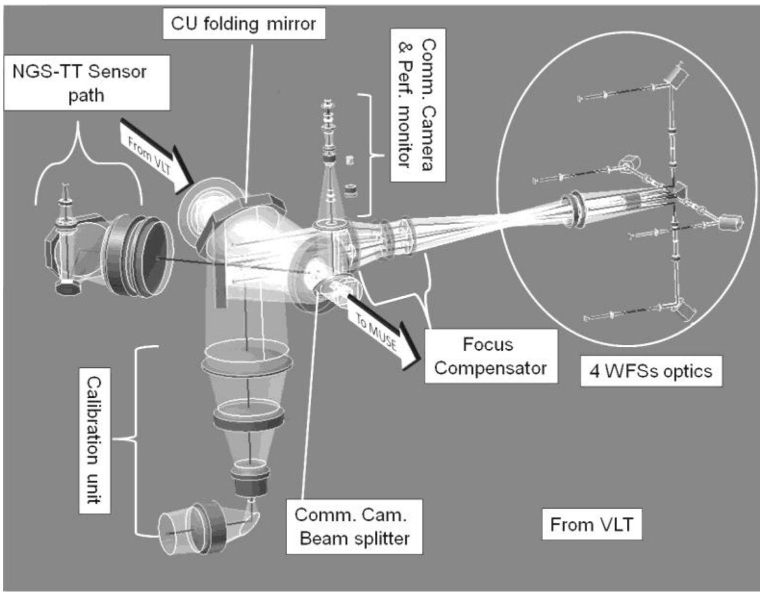


Figure 1: Illustration of the optics foreseen for the GALACSI AOF (courtesy of ESO).

The GALACSI optics will use 4 sodium Laser Guide-Stars launched from the centrepiece of a Unit Telescope of the VLT and the light re-emitted by the 80-100 km altitude Sodium layer is collected by 4 wavefront sensors (WFS). The slopes measured by the WFS are combined with a real time computer to estimate the wave front error caused by the earth's atmosphere and to calculate the correction applied to the Delegated Service Mode (DSM) observations using the VLT. Central elements of the GALACSI optics are two dichroics that reflect both the 589nm Na line and transmit the spectral range from 465nm to 1800nm (NFM Dichroic) and from 420nm to 930nm (Na Dichroic) shown schematically in Figure 2.

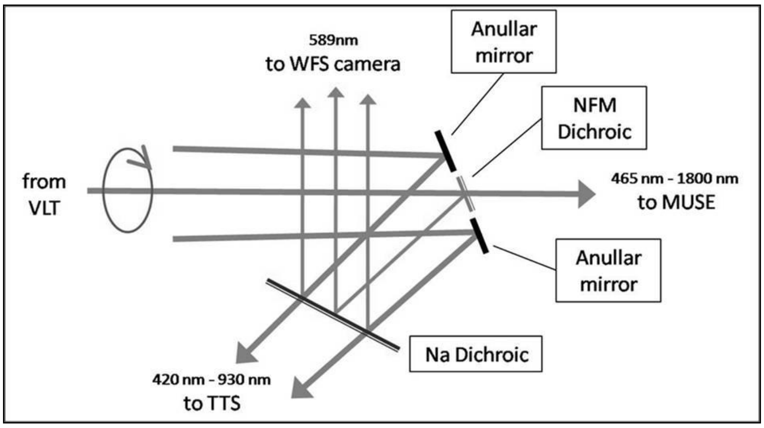


Figure 2: Scheme of the beam paths at the dichroics of the GALACSI optics.

These two dichroics differ only in the transmitted spectral range and the angle of incidence (AOI) but have the same function in reflection. Only a small spectral range close to the 589nm Na line is reflected by reflectance values close to 100 % (Figure 3). The remaining spectral range from 450nm to 1800nm - with a gap between 575nm and 605nm - is transmitted at an average transmittance of 95% (Figure 4). Such a spectral characteristic is typical for a so-called notch filter (NF) defined by a small spectral range of high reflection and a broad spectral range of high transmission. The next section gives a brief introduction to this type of thin-film optical filters, section 3 discusses briefly the design and manufacturing of notch filters, section 4 presents some examples for astronomical observations and section 5 gives some conclusions.

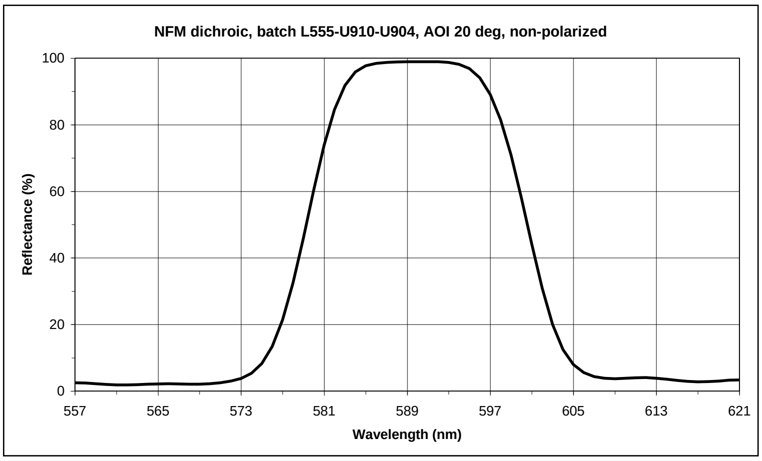


Figure 3: NFM dichroic of the GALCXI optics measured in reflection at 20 degrees AOI, non-polarised.

2 NOTCH FILTERS

Using thin-film optical components with negligible losses, the range of low transmission is in any case a range of high reflection, that is an NF can be seen as rejection filter or as reflection filter. In any case, two different wavelength ranges can be distinguished in the spectral characteristic of such a filter and this fact has defined the term 'dichroic' and also characterises its application in astronomical instrumentation. We start at first with some definitions and clarifications.

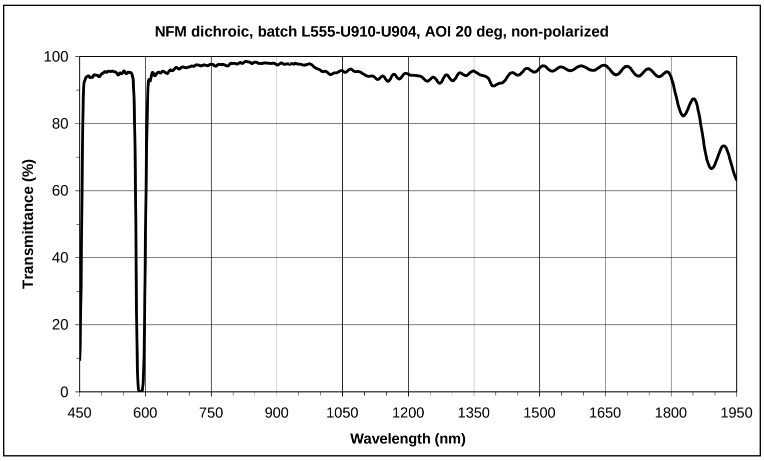


Figure 4: NFM dichroic of the GALCXI optics measured in transmission at 20 degrees AOI, non-polarised.

The term 'notch filter' indicates the existence of a gap or a 'notch' within a broad transmission range. The notch can be seen clearly in a logarithm scale whereas the notch itself stands for a range of high rejection and low transmittance, respectively, or a range of high reflectance. The notch in transmission or reflection stands for both applications but the difference is determined by the required values for the corresponding property: High reflection usually means a value > 99% what results in < 1% transmittance for the remaining rejection. High rejection usually means an optical density > OD 5 or a transmittance < 0.001% what results in a reflectance of 99.999% for the possible reflection. However, the following discussion is restricted to NFs as dichroics that reflect one narrow spectral band, at least, and transmit a broad spectral range.

While a narrow band-pass filter is well defined by the parameter ‘full width of half maximum’ (FWHM), the situation for an NF is more complex. A commonly used NF characterization is illustrated in Figures 5a and 5b. Figure 5a shows the typical NF characteristic with a narrow blocking range around the reference wavelength λ_0 and a pass band from λ_1 to λ_2. The transmittance within the pass band has to be very smooth with a defined pass band minimum. Figure 5b shows the typical notch characteristic with decibel as transmittance unit. The notch is positioned in a way that the 'notch depth' - defined as the transmittance 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.

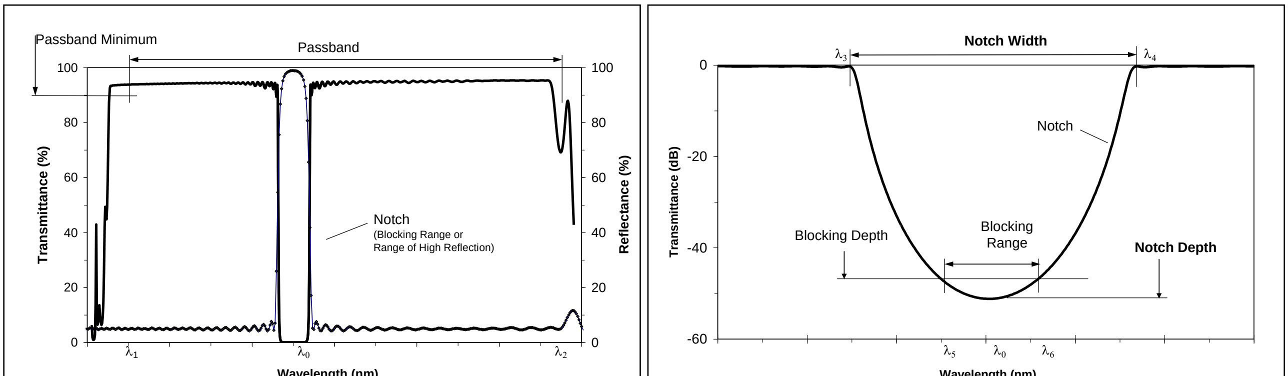


Figure 5a (left): Single NF characteristic with the parameters passband, passband minimum, and blocking range. **Figure 5b (right):** NF characteristic with the definition of the parameters notch width, notch depth, blocking range, and blocking depth.

The notch width depends exclusively on the ratio of the maximum and the minimum of the refractive indices used for the filter design whereas the notch depth depends both on the ratio of the refractive indices and the number of layers or the overall thickness of the filter design. Figure 5b also shows the basic correlation between notch width and notch depth and illustrates a special notch problem: The deeper the notch depth and the smaller the notch width shall be the more layers are required or the thicker the filter will be. This interdependency of notch width and notch depth has to be considered in the design of an NF to check the required number of layers and the overall thickness, respectively, and to check its feasibility.

Using the term rugate in optics, a structure is described that involves a regular cyclic variation of refractive index resembling a sine wave. Such a structure has the basic property of reflecting (or rejecting) a very narrow spectral range and transmitting all others, without the higher-order reflection bands. In this sense, a rugate filter is the ideal NF and rugate designs with small index contrast and apodisation features are well known in the literature.[4] However, the required deposition of gradient index layers or so called flip-flop structures to achieve the sine profiles in the index variation is very complicated and results in very thick layer stacks that require very long deposition times up to 50 hours per filter.[5-7] We use the matrix formalism and the theory of equivalent layers to simulate the performance of a notch filter.[8] Figures 6a and 6b show an example of a rough estimation for the notch characteristic. The parameters of the required notch filter shall be a high reflection range around the reference wavelength of 589nm with a reflection value > 99% and a notch width not exceeding 30nm between 574nm and 704nm. Such a rough estimation provides a design

$$(8H\ 195L)^{50}$$

where the exponent stands for 50 periods of the sequence within the brackets, that are 8nm Ta_2O_5 as high-index material H and 195nm SiO_2 as low-index material L, with an overall physical thickness of 10.2µm. Figure 6a shows the required performance in principle and Figure 6b shows that a smoothing of the ripples close to the notch at 589nm is required what can be easily achieved in a second design step. The next section discusses some requirements and problems occurring in the design and manufacturing of such NFs.

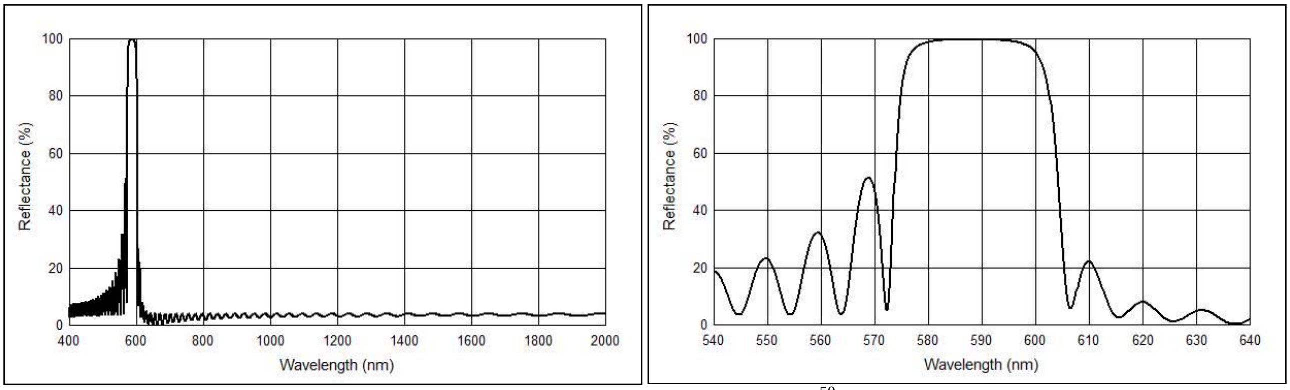


Figure 6a (left): Calculated NF transmittance characteristic with a simple $(8H\ 195L)^{50}$ layer sequence, **Figure 6b (right):** Calculated notch filter reflectance characteristic as with Figure 6a (see text).

3 DESIGN AND MANUFACTURING OF HIGH PERFORMANCE NOTCH FILTERS

Rugate designs using a small index contrast and apodisation are well known in the literature.[9] The required deposition of gradient index layers or so called flip-flop structures is very complicated and difficult to manufacture. Actually hybrid designs of gradient layer designs with higher order and/or multiple thickness ratios and including 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 single and multiple NFs are typically produced by ion-beam sputtering which results in a very long deposition time due to both the thick layer stacks and the low deposition rate of ion-beam sputtering.[10]

Our approach of equivalent layers for the second refractive index leads to relatively thin layer stacks. Moreover the applied deposition technologies of plasma ion-assisted deposition (PIAD) and plasma-assisted reactive magnetron sputtering (PARMS) lead to a reasonable deposition time. The single notch filters for the VLT and the GREGOR telescope have been manufactured using a SyrusPro box coater with the Advanced Plasma Source (APS) technology that is preferred for stable thin-film optical filters since the end of the last century.[11,12] Being the latest monitoring technique, broadband monitoring (BBM) is applied to control the multilayer stack.[13] In this technique, the optical thickness control of the multilayer stack is done directly on the calotte close to the deposited substrates in an intermittent measurement mode on a monitoring glass. In any case, the accuracy for the thickness control has to be in the order of 0.5nm as absolute value and the complete deposition process requires stable conditions over more than 20 hours process time.

The highest-performance multi notch filters are manufactured using the HELIOS magnetron sputtering tool with PARMS technology and broadband intermittent monitoring.[14,15] Figure 7 shows schematically the deposition and monitoring principle of the HELIOS tool. The principle of PARMS technology is the combination of dynamic reactive magnetron sputtering with partial pressure control and a reactive assist process with a plasma-source. Substrates or substrate carriers are loaded on to the substrate turn table via a load lock. By rotation, thin sub-stoichiometric oxide layers are deposited and transferred to non-absorbing oxide layers by the reactive assist process. Meanwhile, the HELIOS sputtering technology enables the deposition of thin-film optical filters with up to 300 layers and an overall thickness of 30µm. Of course, these novel thin-film optics do have some disadvantages, too, such as the big amount of intrinsic compressive stress within the layers or an remarkable stray light of the thick stacks. Anyway, these issues are subject to further research and development in theory and practice of thin-film optics.

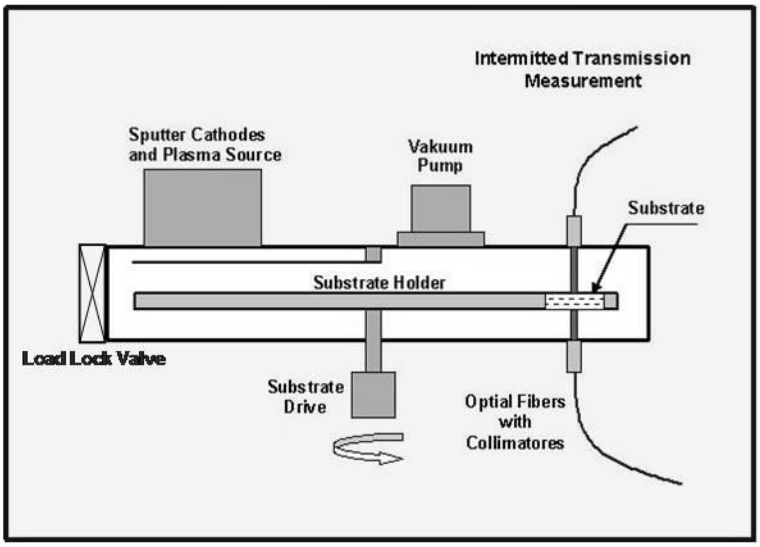


Figure 7: Principle of the PARMS technology and the broadband wavelength intermittent monitoring at the HELIOS sputtering tool (courtesy of Leybold Optics).

4 NOTCH FILTER APPLICATIONS

Apart from the above-mentioned NF as Na dichroic in the GALACSI optics of the VLT's AOF we present a similar application of an NF for the novel GREGOR telescope. GREGOR is the new 1.5m solar telescope currently assembled and tested at the Teide Observatory on Tenerife, Spain. The telescope is designed for high-precision measurements of the magnetic field and the gas motion in the solar photosphere and chromosphere with a resolution of 70 km on the Sun, and for high resolution stellar spectroscopy. Figure 8 shows the optical path through the complete telescope and Figure 9 is a real imaging inside the instrument room of the telescope.

At the end of the 'telescope path' (see Figure 8 or Figure 9, there are a lot of scientific instruments and also a special wavefront sensor that works at 500nm. Only a small spectral band of about 10nm to 15nm around 500nm should be used for this WFS, whereas the radiation at the other wavelengths from 360nm to 2300nm should not be influenced by the beam splitter. As a fixed point, the output coupling should be designed geometrically at 90°. Usually, a beam splitter cube can be used where the coating is inside the cube between two cemented prisms under an angle of incidence of 45°. But theoretically it is not possible yet to split a narrow spectral band by this optical arrangement because of the remarkable polarization splitting under oblique incidence inside a glass/glass boundary. We used an optical arrangement combining a pentaprism with a 60° coupling prism. Figure 10 shows a schematic of this optical design. However, this design of a dichrioic beam splitter requires five different coatings on surfaces A to E.

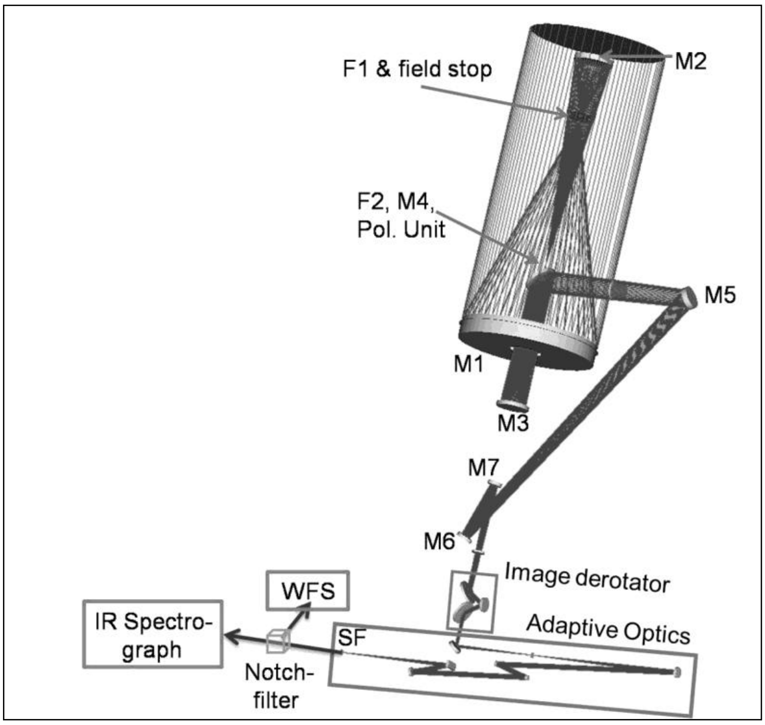


Figure 8: The optical design of the GREGOR telescope with a notch filter at the end of the optical path as a first beam splitter (courtesy of KIS).

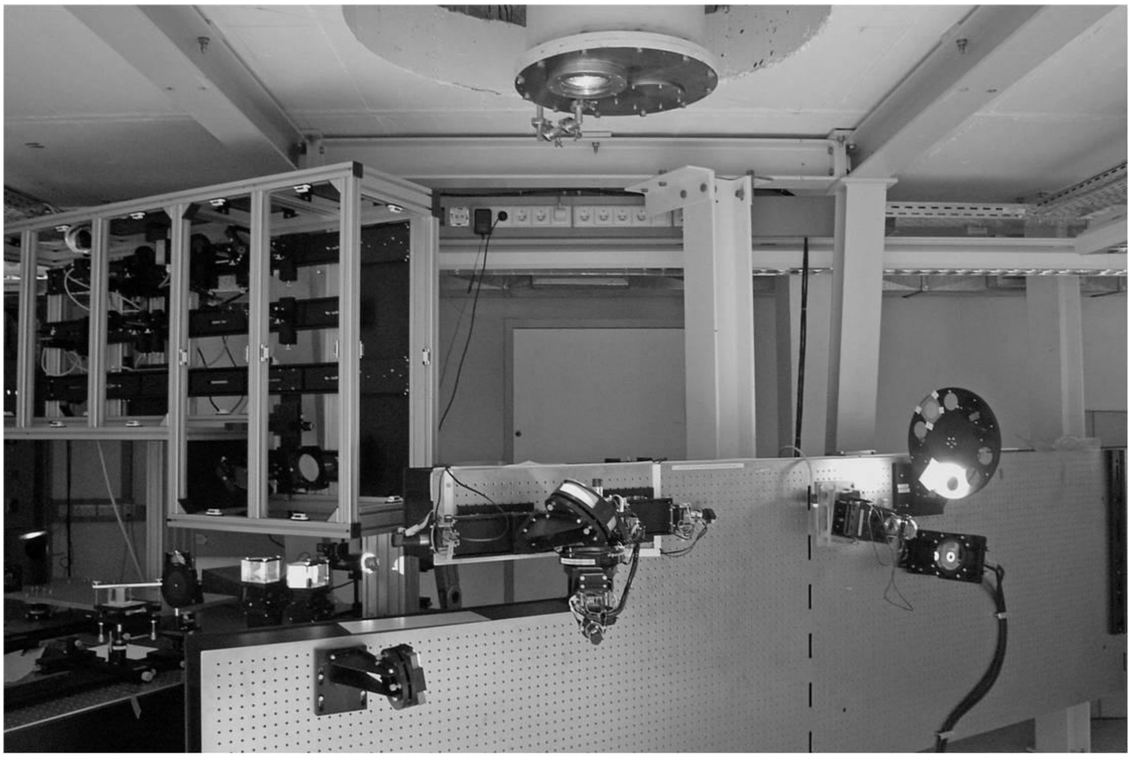


Figure 9: The instrument room of the GREGOR telescope with the beam splitters at bottom left (courtesy of KIS).

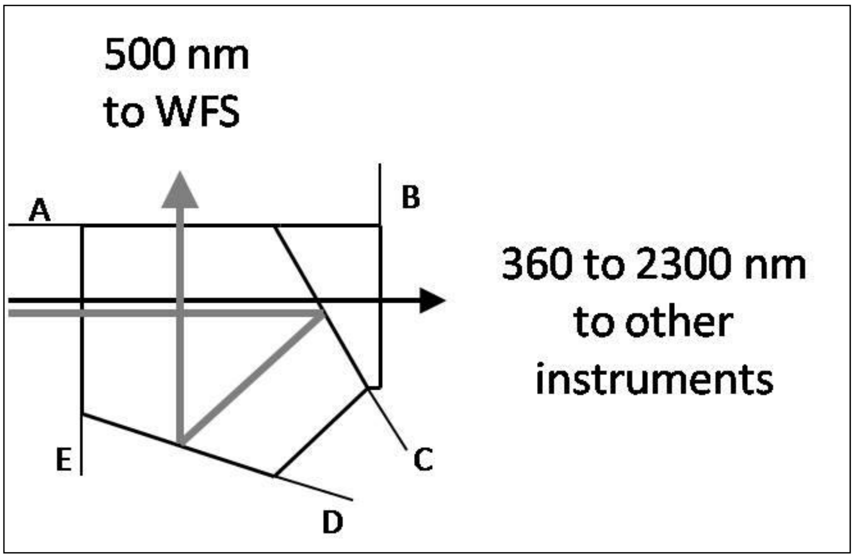
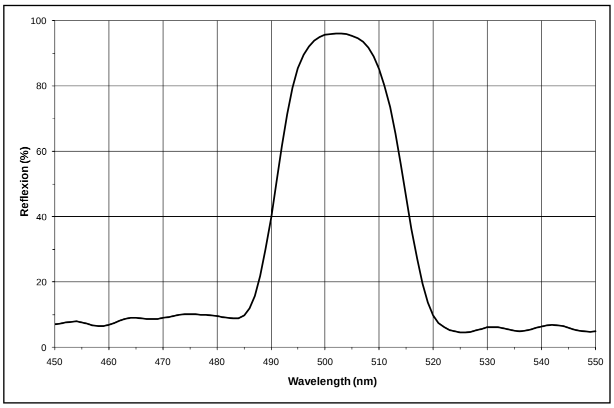


Figure 10: Schematic of the optical design of the 500nm beam splitter, the lines with the capitals A to E mark the different faces at the prism group (see the text).

Face E indicates the entrance face with an anti-reflection coating for the complete spectral range. The transmitted beam leaves the prism-group through face B influenced only by the internal face C between the two cemented prisms where the notch filter is located. Face B is also AR coated. Only a small spectral range around 500nm is reflected at face C at 22.5 degrees AOI with a reflectance value > 98%. This beam is again reflected by nearly 100% at face D at 22.5 degrees AOI and then it leaves the prism through face A towards the wavefront sensor. Face A is again AR coated for 500nm. Figure 11a shows the reflection peak at 502nm and Figure 11b shows the measured spectral characteristic within the complete spectral range from 350nm to 2300nm and. The gap in transmission or the notch width is about 35nm between 485nm and 520nm and the complete spectral range up to 2300nm is transmitted at an average > 90%.



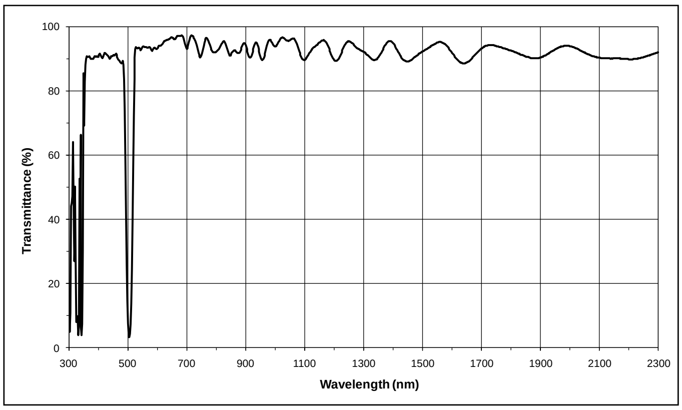


Figure 11a (left): 500nm beam splitter measured in transmittance through the complete prism-group. **Figure 11b (right):** 500nm beam splitter measured in reflection at a witness sample.

Not yet an astronomical application but an interesting UV-NF is located at 218nm and consists of two parallel plates that reflect a spectral band around 218nm and rejects the residual spectral range up to 500nm completely. Figure 12 shows the schematic optical design with 6 reflections at 15 degrees AOI between the parallel plates. Due to a reflectance value of 98.3% at 218nm, 90% of the incoming radiation at 218nm is 'transmitted' through this special NF arrangement and due to a transmission < 5% per reflection, the final radiation from 230nm up to 500nm is decreased to a value < 10^{-8} (Figure 13a and 13b).

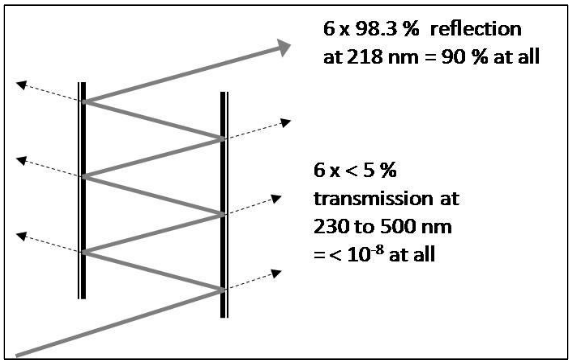
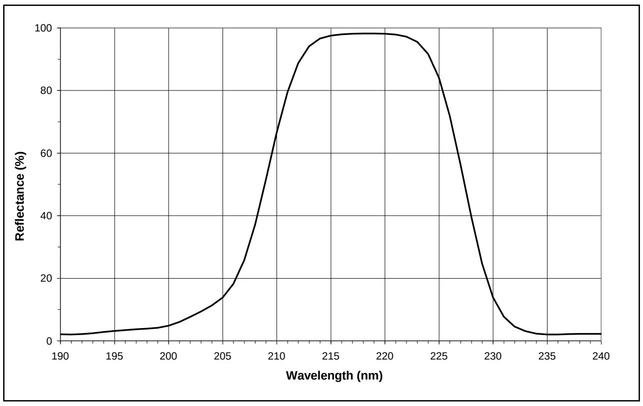


Figure 12: Schematic optical design with 6 reflections at 15 degrees AOI between two parallel plates deposited with the 218nm NF (see text).



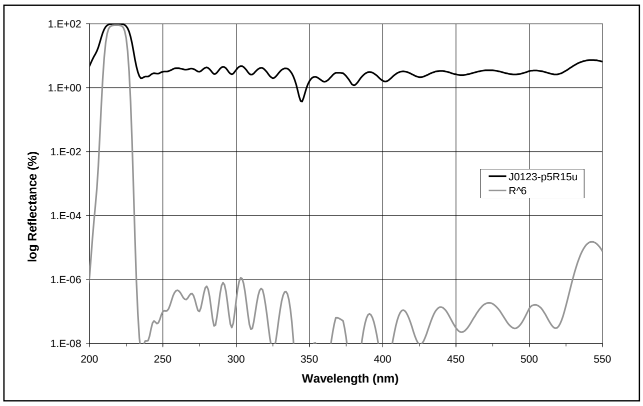


Figure 13a (left): 218nm NF measured in reflectance at a single plate. **Figure 13b (right)**: 218nm NF reflectance in logarithm scale, at a single plate and after 6 reflections inside the two reflection plates.

Finally, a quadruple NF for an application in fluorescence spectroscopy shall demonstrate the actual possibilities provided by NFs and the state-of-art of their manufacturing technology. Figure 14 shows the measured and the calculated performance of such an NF filter with four notches: one at 405nm, one at 488nm, one at 561nm and one at 639nm. The filter design consists of 210 layers of tantala and silica with an overall physical thickness of 19.5µm. The thinnest layer is 4.0nm and the thickest one 383nm. This filter is a sample that was taken directly from the daily serial production at Optics Balzers Jena.

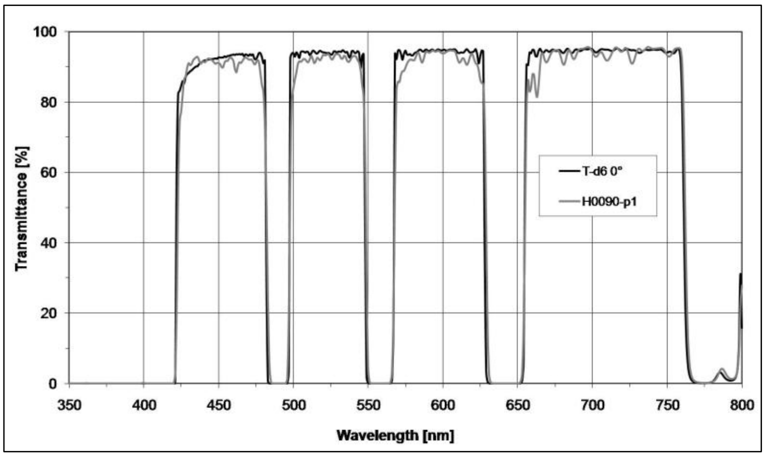


Figure 14: Comparison of measured (H0090-p1) and specified transmittance (T-d6 0°) of the multi NF based on Ta_2O_5 / SiO_2 for AOI 0°. In all four notches or reflectance bands the blocking range is better than OD4.

5 CONCLUSIONS

In this paper we have demonstrated the experimental realization of high-performance notch filters based on our approach of replacing the second refractive index by layers consisting of H/L materials with high index contrast. This leads to a minimum multilayer stack thickness in combination with very thick and very thin layers. To estimate the manufacturing costs of a notch filter, we defined the parameters notch width and notch depth to characterize a notch filter in a novel manner. Applying plasma-IAD using a SyrusPro box coater with APS technology, such single notch filters can be manufactured but with limited yield. High-performance single and multi notch filters can be manufactured more effectively with high yield and reproducibility applying plasma-assisted reactive magnetron sputtering and broadband optical monitoring in an HELIOS sputtering tool. As examples, we have presented single notch filters for 589nm which are part of the GALCSI optics at the VLT and, respectively, for 502nm that are for the novel GREGOR telescope. Additionally, we have presented a 218nm notch filter in a multiple reflection arrangement and have demonstrated the possibilities provided by state-of-the-art deposition technology applying the magnetron sputtering technique on a quadruple multi notch filter for the visible spectrum.

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