Manufacturing and characterizing of all-dielectric band-pass filters for the short-wave infrared region

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ABSTRACT

Besides the typical channels in the visible and near infrared spectrum, optical remote sensing of the earth from air and space utilizes also several channels in the short-wave infrared spectrum from 1000 nm to 3000 nm. Thin-film optical filters are applied to select these channels, but the application of classical multiple-cavity band-pass filters is impossible. Because of their additional blocking elements they are disallowed due to geometrical or other non-optical reasons. Within the sensitivity region of an MCT detector as typical detector device, the selection and blocking of radiation by the filter has to be provided by a single multilayer system. The spectral region of the SWIR as well as blocking width and depth require necessarily designs with overall thicknesses of more than 20 µm, with layer numbers up to 100. SiO_2 and TiO_2 were used as thin-film materials deposited with reactive e-beam evaporation under ion assistance in a Leybold SyrusPro box coater. A special challenge was the thickness measurement of the thin films by an optical broadband monitoring device in the visible range. The results of manufacturing and characterizing of such filters are presented by three examples for the center wavelengths of 1375 nm, 1610 nm, and 2190 nm.

Keywords: self-blocking SWIR dielectric filters, Ion-Assisted Deposition, Broadband Monitoring

1 INTRODUCTION

Optical multi-spectral remote sensing of the earth from air and space uses besides various spectral bands in the VIS and NIR (VNIR) region also several channels in the Shortwave Infrared (SWIR) to determine diverse bio-geophysical variables[1,2]. The SWIR channels allow detecting plant drought stress or burnt areas and fire-disordered vegetation e.g.. The so called cirrus filter with a centre wavelength of 1375nm allows the detection of sky cover levels for atmospheric corrections.
The manufacture of interference band-pass filters for the spectral region between 1000 and 3000nm becomes a challenge, if the required optical, environmental or instrument features don’t allow the application of classical multi cavity band-pass filters in combination with discrete blocking elements. The selection and blocking of the radiation then has to be performed by a single optical element. The commonly used MCT (Mercury cadmium telluride - HgCdTe) infrared detectors are very sensitive in the SWIR band. To increase their signal-to-noise ratio to adequate levels, these sensors must be cooled, often to extremely low temperatures.

The SWIR filters are typically assembled as an array of filter stripes in combination with an opaque aperture mask. This array is placed in front of the sensor focal plane – i.e. a deep cooled MCT detector array. So no color glasses and no cemented components are applicable. To inhibit the impact of multiple reflections in the filter substrate, band-pass and blocking both have to be realized at the side of the substrate facing the detector (self-blocking filter design). The opposite surface of the substrate is coated with an AR coating to minimize reflections only.

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To separate SWIR from other VNIR detection channels in the atmospheric window, typically a separate dichroic filter element is implemented in the optical instrument (see Fig. 1). Therefore the rejection requirement of the SWIR band pass filters start typically at 1100nm. The reason for this approach is the spectral position of the first SWIR band at a center wavelength (CWL) of 1375nm placed within a minimum of transmission of the atmosphere[2]. Because of the sensitivity of the detectors a broad filter rejection from 1100 to 2100 or 2700nm is required.

On the basis of three examples of interference filters with CWLs of 1375nm, 1610nm and 2190nm spectral requirements, design and manufacturing technology will be presented. We focus on the technological implementation of spectral requirements. Other aspects like process stability, substrate influence, stray light effects or environmental stability will not be considered here.

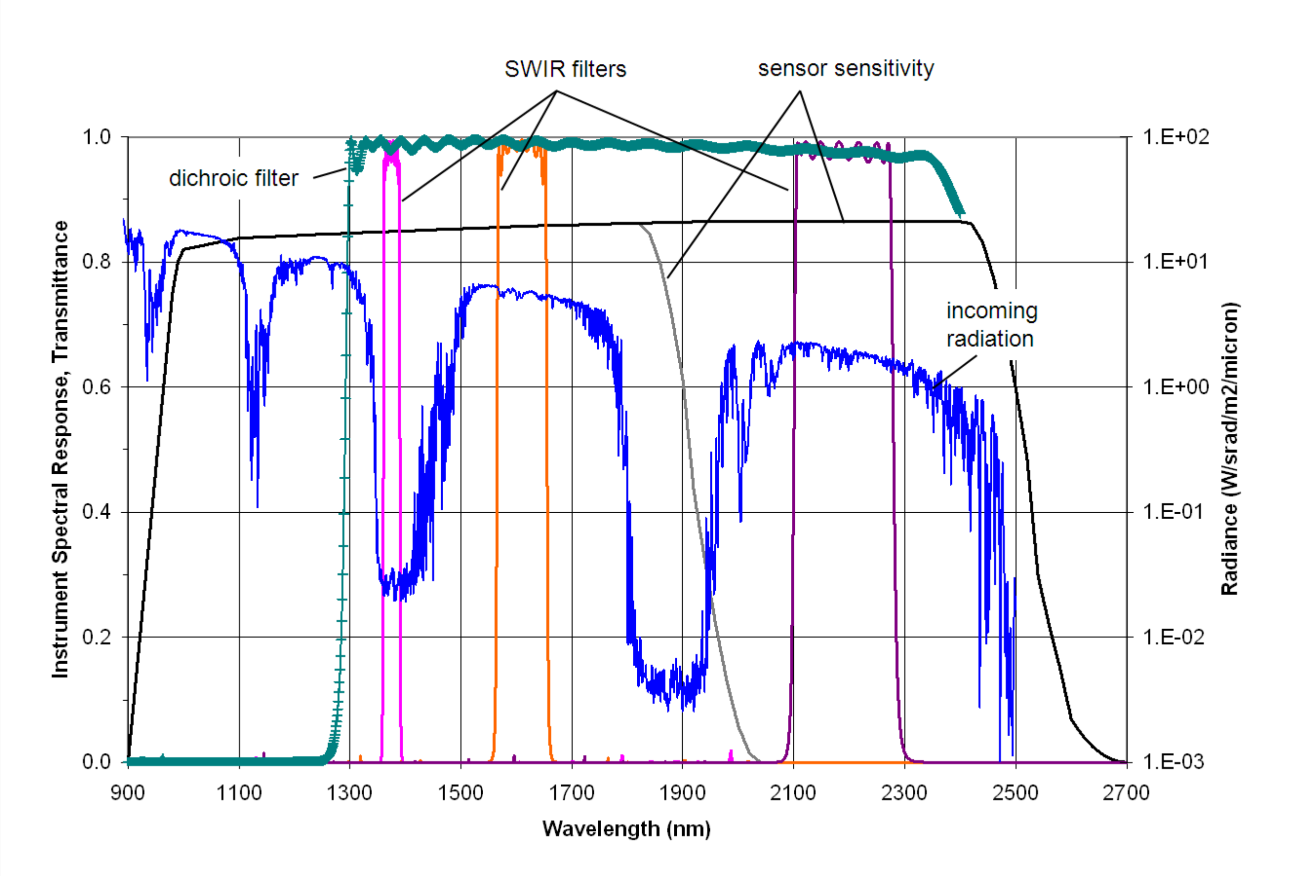

Figure 1. Components of spectral characteristics of SWIR filters: Band-pass filters at 1375 nm, 1610 nm, 2190 nm, incoming radiation, detector sensitivity and dichroic filter (+)

2 REQUIREMENTS

The SWIR spectral region, the required blocking width and depth require multilayer designs with up to 100 layers and lead to overall physical thicknesses of approximately 20µm.
Classical band pass filters[3,4] with a Fabry-Perot and multiple cavity design approaches need a dual sided design (band pass and blocking system on both substrate sides) to achieve broad rejection zones[5].

The filter concept presented here is based on self-blocking all-dielectric multilayer band pass filters. The filter coating realizes both the pass band and the blocking function on one single surface of the substrate.
This design permits broad blocking zones from 1100 to 2100 or 2700nm respectively by enabling additional design freedom from “non regular” layer thicknesses. Latest Thin-Film Design Software (Needle Method) like Optilayer™ thin film software has to be applied here.

The full specification sets value on high transmission at the center wavelength, defined bandwidth (BW) as FWHM, very steep edges and low out-of-band energy amounts down to 10^{-4} out-of-band blocking levels (see Table 1).

Table 1. Subset of band pass filter characteristics

Filter	CWL [nm]	BW [nm]	T_{mean} [%]	Rejection	Band Limit [nm]	Range [nm]
BP1375	1375 ± 5	30 ± 5	> 85	<0.01	1336 - 1412	1100 - 2100
BP1610	1610 ± 10	90 ± 10	>85	<0.01	1532 - 1704	1100 - 2100
BP2190	2190 ± 10	180 ± 10	>85	<0.01	2035 - 2311	1100 - 2700

The rejection or out of band response is defined by a noise/signal ratio where the signal is defined by the transmission within the band limits – which give a spectral width per band slightly broader than the bandwidth BW – and the noise is defined by the transmission outside the band limits and within the range that characterizes the sensor spectral sensitivity. In this case, transmission means the integrated transmittance of the filter weighted by the solar radiance level. This criterion affects the spectral cleanliness of the resulting multi spectral image but it allows also some small spectral peaks outside the band limits and does not require transmittance values less than a defined maximum.

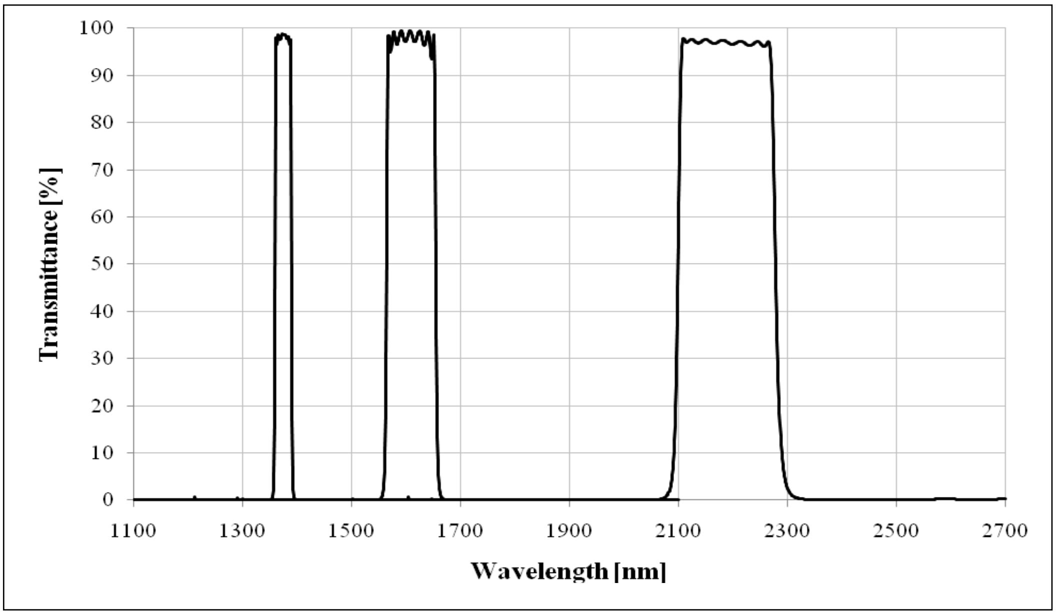

Figure 2. theoretical performance values as a transmittance versus wavelength plot of BP1375, BP 1610 and BP2190

Figure 2 shows theoretical performance values for three SWIR filters. For the BP1375, Figure 3 gives an exemplary thickness distribution graph from design data with 105 layers, overall physical thickness of 22µm and single layer thicknesses as minimum 51nm and as maximum 366nm.

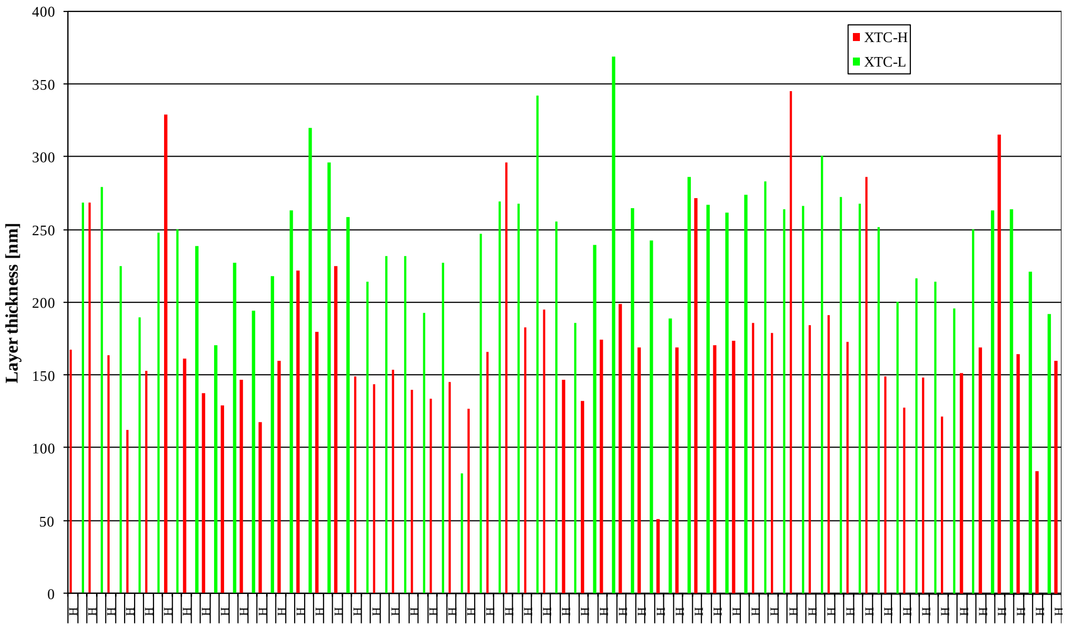

Figure 3. Thickness distribution example: BP1375 with 105 layers, overall physical thickness 22µm, single layer thickness as minimum 51nm, as maximum 366nm

Table 2. filter physical thicknesses (exemplary design versions)

Filter	no of layers	thickness [µm]	L-mat. [µm]	H-Material [µm]
BP1375	105	22.05	12.73	9.32
BP1610	87	18.94	11.05	7.89
BP2190	95	22.43	13.45	8.98

Other than the mentioned spectral requirements the filters have also to withstand diverse mechanical, thermal, radiation (proton and γ radiation) and other impacts. For instance performance has to be guaranteed over a thermal range from 180 to 300K under residual pressure of 10^{-5}hPa (no vacuum/air shift).
These high stability demands require latest deposition technology under ion-assistance.

3 MANUFACTURING

The production of optical filters with such high accuracy requirements to central wavelength, bandwidth and edge steepness demand latest deposition technology. The filter coatings for the SWIR band-passes presented have been manufactured by using SyrusPro box coaters equipped with Advanced Plasma Source (APS). This technology has proved to achieve stable thin-film optical filters since the end of the last century.[6,7]
In contrast to conventional e-beam PVD the plasma assistance allows coatings at lower process temperatures and induces a compaction of the coated layers. Those coatings will not change their optical properties in ambience after the vacuum process by moisture penetration and temperature change (vacuum/air shift).
Standard layer thickness control by quartz crystal thickness monitoring achieves maximum accuracy of about 1-2%. For production of the described SWIR filters with their requirements to wavelength, bandwidth and edge steepness this uncertainness is not tolerable.
Moreover because of the highly sophisticated application such filter coatings are manufactured in very small-scale series productions. There are few opportunities for optimization cycles. The combination of plasma assisted e-beam

evaporation with broad-band spectra photometric thickness monitoring is a useful technology for the manufacturing with an affordable effort.

All filters are based on SiO_2 and TiO_2 layers deposited by ion assisted electron beam evaporation. Because of the spectral separation of VNIR and SWIR bands by a dichroic filter no blocking in the NIR and VIS is needed for the SWIR filters. Thus layer thickness control during deposition can be realized by optical broad band monitoring (BBM)[8] in the wavelength region from 420 to 1020nm.

With this monitoring technique the optical thickness control of the multilayer stack is performed directly on the calotte close to the substrates position. The measurement is carried out intermittent on a monitoring glass per single calotte rotation (0.5Hz). One transmittance curve consists of three single measurements: a dark-current spectrum, a reference measurement without any substrate and the sample spectrum itself.

The growing layer thickness is calculated by comparison of the modeled with the measured spectra.

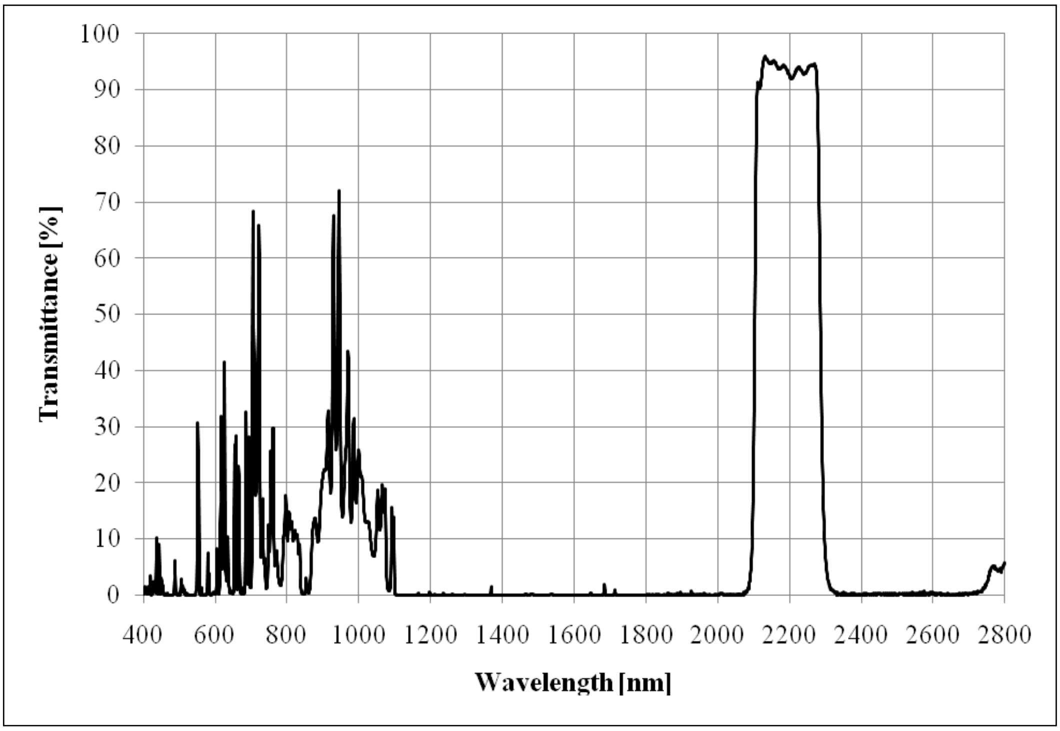

Figure 4. Spectral characteristic of SWIR BP2190 with blocking range from 1100 nm to 2700 nm and monitoring range from 420 nm to 1020 nm

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 up to 20 hours deposition process time. Successful generation of difficult coatings requires accurate knowledge of optical material constants. The design of the coatings is based on experimentally determined material data. In real production situation that values vary for different operating conditions (coating parameters), chamber maintenance status or even during deposition. The in situ monitoring in combination with thin film design software allows re-optimization during coating run. Deposition over such a long time requires monitoring sample changer mechanism. Because of the gap between monitoring and pass-band wavelengths a proper extrapolation of dispersion data is essential[9]. The tolerable index mismatch must not exceed 0.1%. Otherwise the desired band width will not be realized, though a mismatch in band position (CWL) could easily be corrected by a factor. With the BBM applied here manufacturing can be carried out direct from design data without the necessity of validation runs.

4 RESULTS

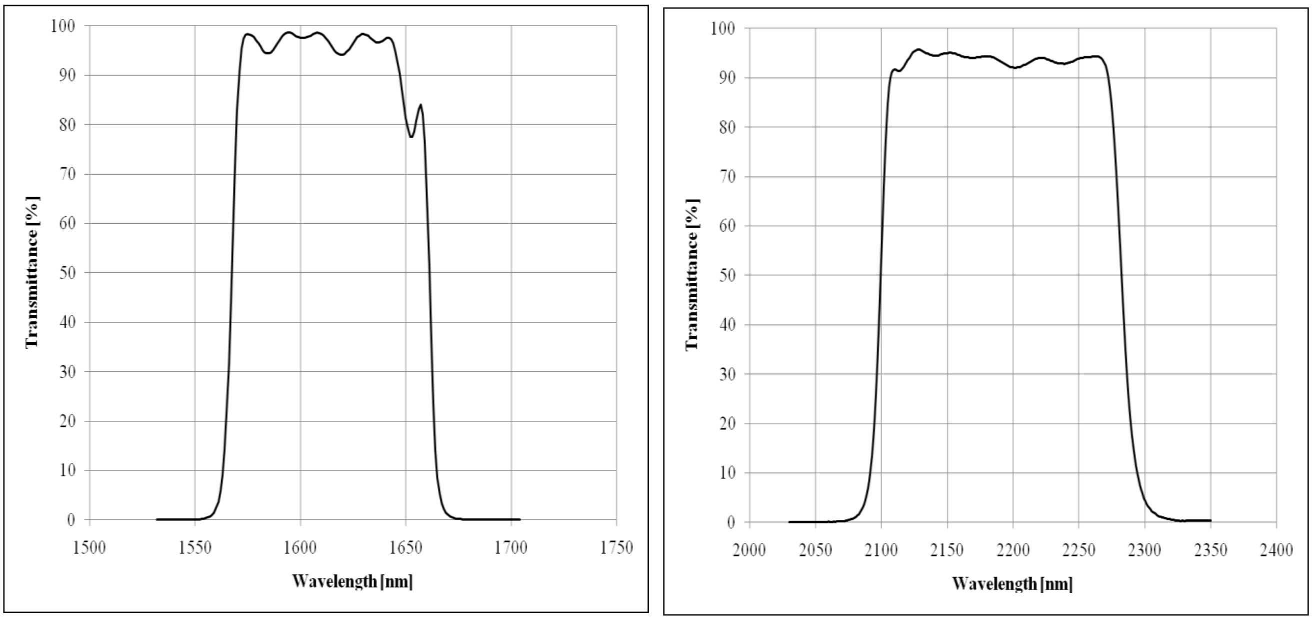

Figure 5. Measured spectral characteristics of BP1610 and BP2190, deviated CWL 1611.1 and 2190.9nm, deviated BW 93.5 and 183.1nm

Figure 5 presents the filter transmission curve for BP1610 and BP2190 filter substrates. Figure 6 demonstrates the corresponding response values in the blocking region for a BP2190 filter. Figure 7 demonstrates the homogeneity within one run for 10 filters.

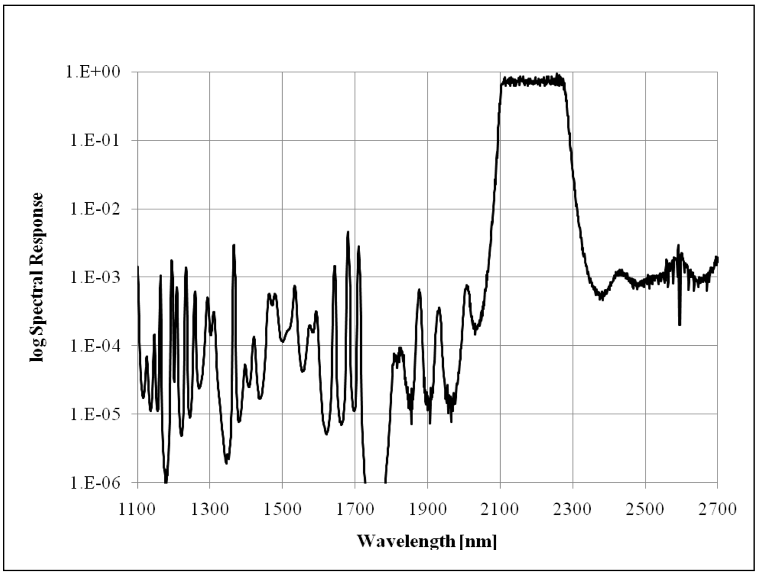

Figure 6. Measured log spectral response for BP2190 integrated response 0.42%

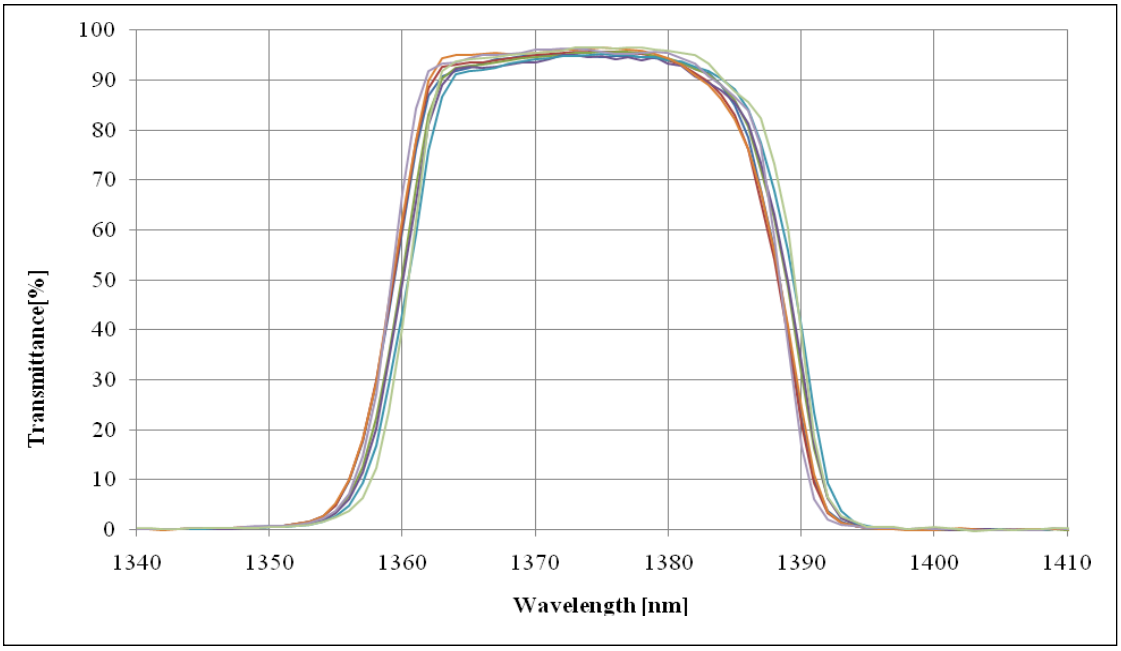

Figure 7. Measured transmittance of 10 BP1375 filters centre wavelength = 1374.5 +/- 1.2 nm, bandwidth = 29.2 +/- 0.8 nm

5 CONCLUSIONS

In this paper we have demonstrated the experimental realization of high-performance SWIR band pass filters. Applying plasma-IAD using a SyrusPro box coater with APS technology and broad-band monitoring allows a direct from the design data manufacturing. It is possible to monitor the film thickness during the deposition process of such SWIR filters by an optical broadband monitoring technique in the visible spectral range although there is not any spectral requirement in this range. These SWIR filters must be self-blocked over the spectral sensitivity range of the detector (usually of HgCdTe type) as single-face coating. Blocking width and edge steepness of the pass-bands require unique filter designs with up to 100 layers and the spectral positions result in about 20 µm overall thicknesses. Needle method as thin-film design software, a deposition technology under ion-assistance and optical broadband monitoring on the calotte as monitoring technique are requested essentially to manufacture the filters and to fulfill all the optical and non-optical requirements.

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