Spatially resolved spectroscopy for non-uniform thin film coatings: comparison of two dedicated set-ups

A.Krasilnikova[1], A.Piegari[1], M.Dami[2], L. Abel-Tiberini[3], F.Lemarquis[3], and M.Lequime[3]
[1]*Optical Coatings Group, Advanced Physics Technologies Division, ENEA,via Anguillarese 301, 00060 Roma, Italy*
[2]*Galileo Avionica S.p.A.,via A. Einstein 35, 50013 Campi Bisenzio (FI), Italy*
[3]*Institute Fresnel, UMR CNRS 6133, Domaine Universitaire de Saint Jérôme, 13397 Marseille Cedex 20, France*
annak@casaccia.enea.it, piegari@casaccia.enea.it, michele.dami@galileoavionica.it
laetitia.abel@fresnel.fr, frederic.lemarquis@fresnel.fr, michel.lequime@fresnel.fr

ABSTRACT
For characterisation of non-uniform thin film coatings optical measurements should be performed with spatial resolution often much higher than that of conventional spectrophotometers. Here we present two different instruments constructed for transmittance and reflectance measurement of spatially non-uniform coatings. One of the setups is based on localized light distribution with a help of calibrated apertures, mapping needing sample displacement, while the other setup acquires the sample map 'at-once' with a CCD camera, spatial resolution being given by the pixel size. The spatial resolution ranges from 100 μm up to 2 mm for the first instrument, and is 30 μm for the second one. The spectral resolution of the first setup is about 0.5 nm in the range from 400 nm to 1700 nm, while for the second instruments it is 0.1 nm in the range 400-1000 nm.

Besides the real optical performance of an optical device in terms of its spatially variable transmission and reflection, a 'mapping' of the thickness and refractive index of a single layer coating can be achieved. Comparison of the results obtained with these two instruments is given for two examples of coatings. The proposed instruments are useful tools for characterisation of both intended and undesired non-uniformity of optical coatings.

Keywords: non-uniform thin film, spectroscopy, spatially resolved measurement

1. INTRODUCTION
Spatially resolved transmittance and reflectance measurement is of crucial importance for characterization of optical coatings with characteristics changing over the coating surface. Such variation can be intentional, as in the case of linearly variable filters [1], where the optical properties variation provides specific performance of the device. Often, however, it is necessary to maintain a coating spatial uniformity along the device surface so variations of it thickness or/and optical constants are not desired and must be checked. This is the case of the major part of coatings, such as different types of filters, dielectric mirrors etc.

If the variation of the optical parameters on the coating surface is "smooth" enough, commercial spectrophotometers can be used to perform checks at several distant points of the coating. The measured value is therefore an average over the area of the beam spot on the sample that is as large as several square millimetres. It is evident that for small samples or for the samples having spatial features of size smaller than the test beam cross-section, commercial instruments can not be used.

Here we present a comparison of two setups dedicated to spatially resolved spectrophotometry. One of the setups is based on the localized light distribution with a help of calibrated apertures, while the other setup acquires the sample map 'at-once' with a CCD camera. Their performance is compared in terms of spatial and spectral resolution, easiness to handle with and usefulness for different applications.

Optical Fabrication, Testing, and Metrology II, edited by Angela Duparré, Roland Geyl, Lingli Wang,
Proceedings of SPIE Vol. 5965 (SPIE, Bellingham, WA, 2005) · 0277-786X/05/$15 · doi: 10.1117/12.625183

2. SPECTROMETER FOR LOCALIZED PHOTOMETRY

This spectrophotometer was designed to evaluate uniform as well as spatially variable optical coatings. Detailed description of this setup is given elsewhere [2] and its schematic representation is given in Fig.1. At the entrance, the system is illuminated by a quartz-halogen light source coupled in a 200 µm diameter core optical fibre. At the output, the spectral analysis is performed by an optical spectrum analyser operating from 400 to 1700 nm. The sample is placed in between, as well as a set of calibrated apertures that are imaged on the sample surface without magnification in order to select the diameter of the measured area (from 100 µm to 2000 µm). When no calibrated aperture is used we obtain the largest measurement area (2mm diameter) which is in fact the image of the entrance fibre with a magnification of ten due to the entrance optical system.

At present time two channels are available, either for the reflected or transmitted beams, which are finally connected to the spectrum analyser by the way of a moving mirror which allows the selection of each channel without disconnecting the exit fibre, in order to enhance measurement repeatability. Reflectance and transmittance channels are both composed of a 400µm diameter core fibre. Both are the image of the measurement area defined on the sample using a similar optical system as the one used for the entrance fibre (magnification of one tenth). The images formed by this way are at most 200 µm diameter disks (corresponding to the core of the entrance fibre) when no aperture stop is used. The larger diameter used for the reflectance and transmittance fibres allows a more convenient alignment. In the same way the core diameter of the exit fibre is 600 µm. At last all the optical systems used between optical fibres are telecentric ones.

The spectral resolution is between 0.5 and 5 nm, according to the diameter of the optical fibre that is connected to the spectrum analyser and which plays the role of the entrance slit of the monochromator. The sample is motorized along two translations stages so that we can perform automatic mapping on a 60 x 25 mm^2 area. The position accuracy is typically 3 µm.

A reference photodiode, placed between the entrance fibre and the sample, allows correcting the measurement from light source fluctuations. This reference photodiode combined with a periodic calibration on a reference sample (every three hours) allows obtaining a standard deviation of about 10^{-4} for a measurement area of 2 mm the measurement repeatability, including the sample displacement, is about 10^{-3}.

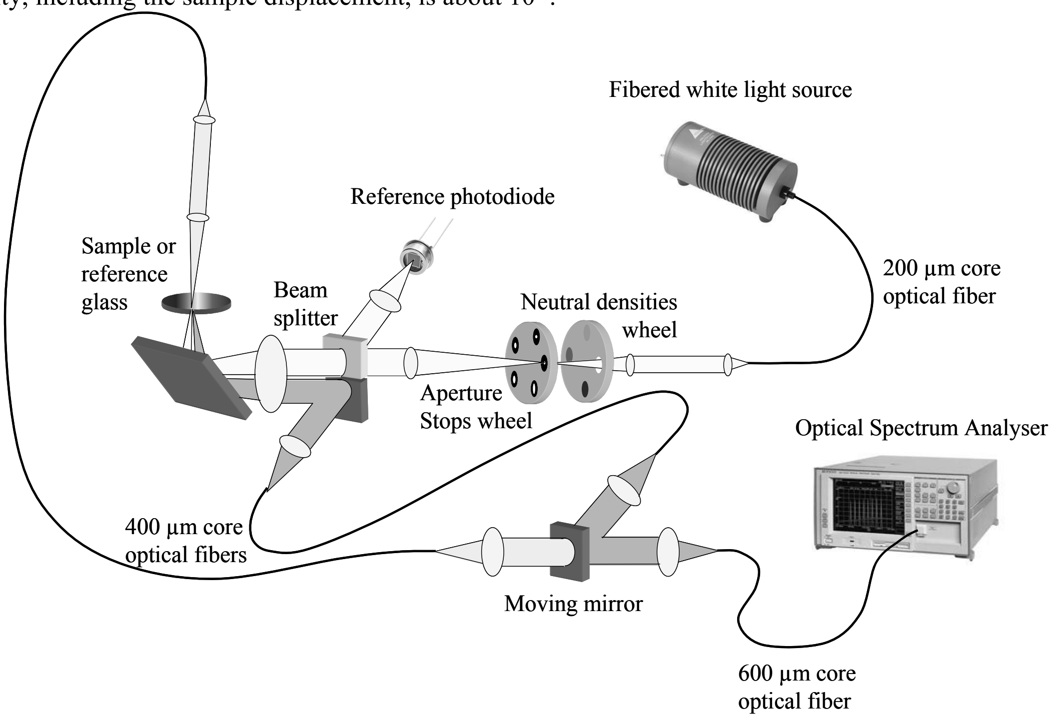


Figure 1. Schematic representation of the spectrophotometer. Calibrated apertures permit to define on the sample a probing zone diameter from 100 µm to 2000 µm. Spectral range extends from 400 to 1700 nm and resolution from 0.5 to 5 nm

3. CCD-BASED SETUP FOR SPATIALLY RESOLVED SPECTROPHOTOMETRY

A sketch of the CCD-based setup is shown in Fig.2 and can be logically split in three main parts. The first is the Acquisition System, which includes electronics, detector, dedicated software and PC used to acquire the signal collected by the CCD TH 7890 (512 x 512 pixels 17μm pixel size). The second one is the Optical Ground Support Equipment (OGSE) Control System consisting in its electronic, software and PC used to govern the "stimuli" optical subsystem constructed for uniform illumination with a quasi monochromatic light. The wavelength range is determined by the source choice which is currently a Quartz Tungsten Halogen lamp, its spectral calibration can be considered completed (depending on the transmittance of the optical imaging system) in the range 400÷1000nm. However three turrets of the monochromator with three gratings with efficiency optimised in different spectral range, allow much wider spectral limits.

The third is the Optical Test Set-up that is the optical system used to illuminate a sample and to collect the radiation passing though it. This optical subsystem works by imaging the diffuser surface on the sample surface. So this part of the optical bench realises the "sample illumination" function. The specimen surface is then optically relayed on the CCD active surface, which collects the signal.

To guarantee the same measurement conditions for each sample point, especial efforts must be made to provide uniform radiance along the sample surface, as well as to realise a "good match" between the illuminated beam and the collecting beam.

The radiance emitted by the diffuser is spatially uniform: the non-uniformity (Max-Min/Max+Min) is less than 2% on the entire diffuser surface. The illuminating "beam cone" arriving on each sample point has the same aperture for the entire surface because the diffuser is positioned on the doublet focal plane, so the exiting beams will be collimated and the diaphragm will define the pupil of the following relay lens. Diffuser BRDF has been selected in order to guarantee, within the solid angle seen by each sample point, high uniformity of about 2%. The variations of the optical transmission due to different optical paths followed by the beams from diffuser to the sample, introduce a radiance variation of about 2%. Considering all these effects, the radiance arriving on the sample can be considered constant within about 5%. The spectral characteristics of the stimuli radiation: bandwidth and central wavelength are defined by the spectrometer parameters.

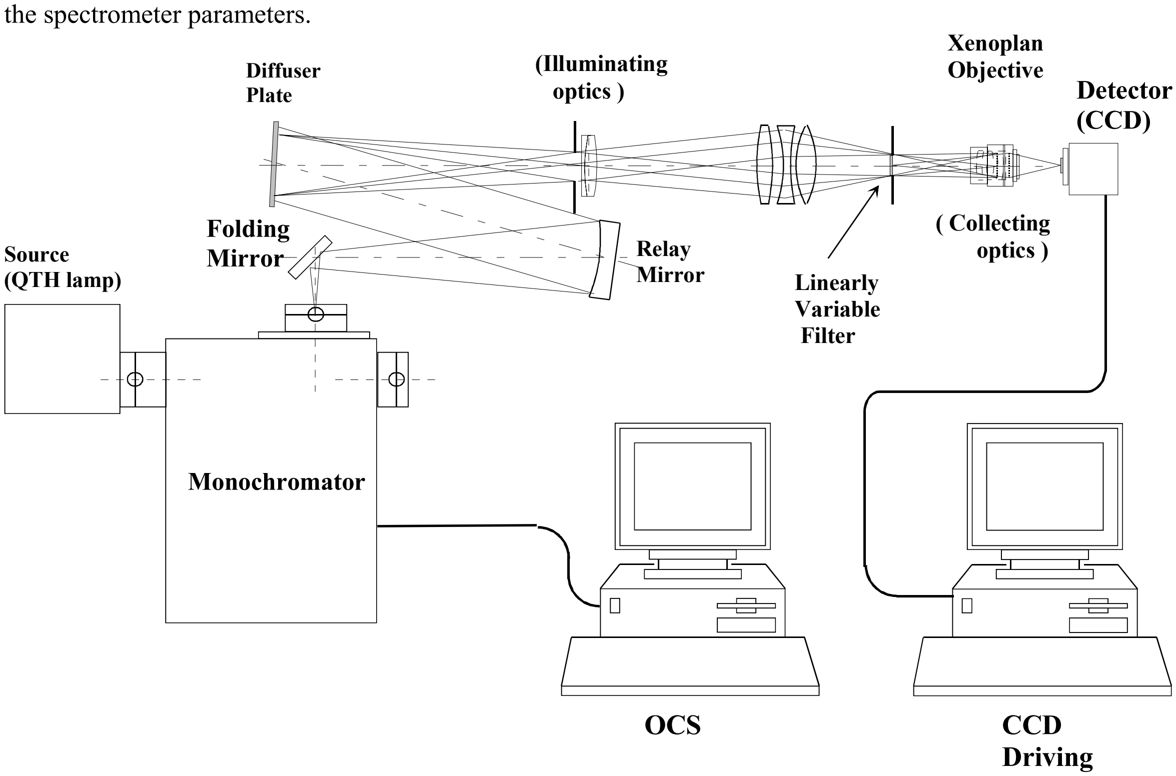


Figure 2. Schematic representation of the CCD-based optical bench

The collecting optical system is the objective Xenoplan 1.9/35 – 0511 @ Schneider that relays the sample surface on the CCD. This lens is mounted in a Finite-Finite configuration in order to match the sample size to the CCD sizes. The designed magnification (nominal value) is 1.75X, in order to guarantee collection of the whole sample surface. With this choice and assuming the sample size above listed, on each pixel falls a spectral band of about 1.8 nm fall on each pixel. The Xenoplan is spectrally corrected in the range: 400 – 1000 nm. Although this objective is not telecentric, the sample illumination optical system has been designed in order to avoid any vignetting and simultaneously to fill with minimum margin the optical aperture of the Xenoplan. In this way, the effects of diffused unwanted radiation have been reduced because not collected by the CCD. The effective Xenoplan magnification depends on the position of the Xenoplan between the sample and the CCD. If this distance changes a new magnification measurement should be carried out. In present configuration the setup permits the transmittance measurement only and the standard deviation for the transmittance values repeatability is about 10^{-2}.

4. MEASUREMENT EXAMPLES AND SETUP COMPARISON

To make comparison between the two setups we chose two samples of multilayer coatings on glass. The first (sample FF_FP) is a narrow-band transmission filter (LVF). The design of the coating is Air/M5 2B M5/Glass, where M5 is a five-layer quarter-wave mirror made with Ta_2O_5 and SiO_2 and 2B a half-wave layer of SiO_2. The transmission peak wavelength (reference wavelength) extends from 440 to 880 nm across the sample on a distance of 20 mm in one direction of the surface and this variation is obtained by a linear gradient of the coating thickness, Fig.3.1. Perpendicularly to the gradient axis, iso-thickness lines are almost straight, Fig.3.2. The component has a square shape, 20 mm each side.

Another sample (G5TS37) is a five-layer quarter-wave mirror made of alternating films of Ta_2O_5 and SiO_2. Similarly to the first sample, its reference wavelength (corresponding to maximum reflectance or minimum transmittance) linearly varies from 235 to 590 nm on 10 mm distance with a gradient of about 35 nm/mm, higher than the previous one. The coating thickness is uniform outside the variation distance of 10 mm and is also uniform in the perpendicular direction on 25mm distance, Figs.3.3 and 3.4.

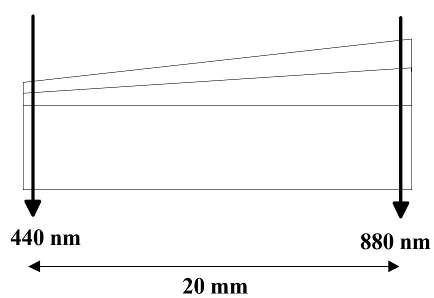


Figure 3.1 Schematic representation (cross-section) of the sample FF_FP

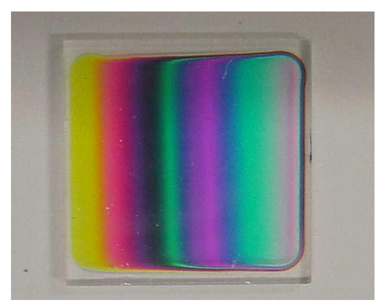


Figure 3.2 Image of the sample FF_FP

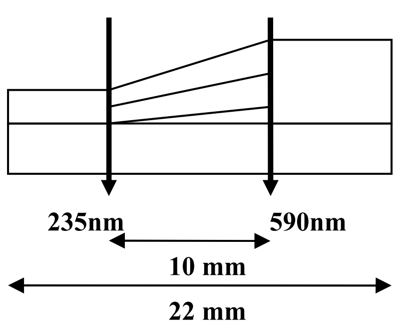


Figure 3.3 Schematic representation (cross-section) of the sample G5TS37

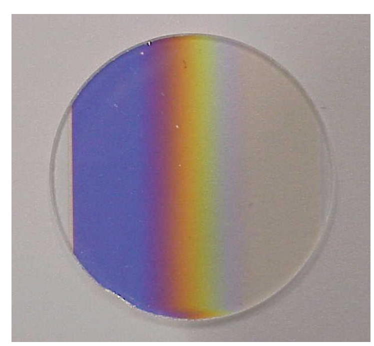
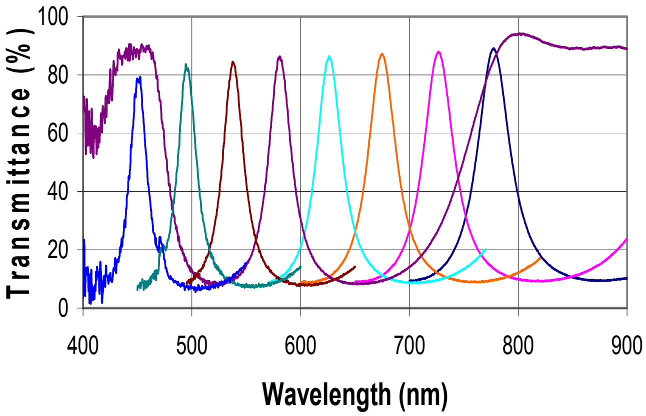


Figure 3.4 Image of the sample G5TS37

Let's start from the first sample that requires a good spatial and spectral resolution. With the first set-up, the characterization of this variable filter is achieved with a measurement area of 200 µm diameter (spatial resolution), and a spectral resolution of 5 nm. The spectral range goes from 400 nm to 900 nm on a 14*14 mm square surface. The distance between two adjacent points is about 2 mm and so 64 points were measured. Transmitted spectral performance measured for 8 point aligned on the gradient axis, are drawn in Fig.4.



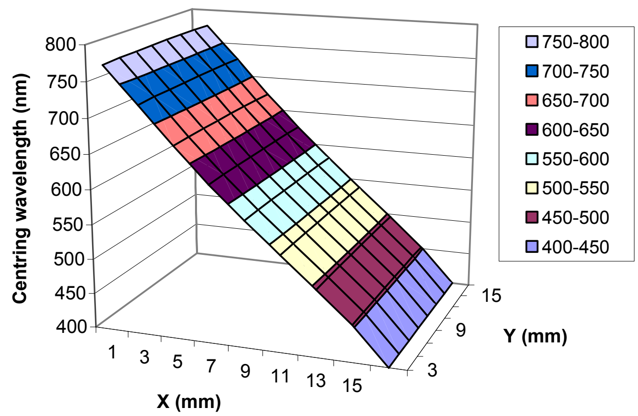


Figure 4. FF_FP filter: Spectral shift of the transmitted peak through points 2mm-spaced points

Figure 5. Mapping of the spectral shift of the transmitted peak over a square of 14*14 mm for the LVF obtained with the first set-up

The slight drop of the peak transmittance toward short wavelengths is due to a combination of both the spatial averaging over the measurement area and the spectral averaging due to the spectral resolution. Noise occurring at shorter wavelengths comes from the low flux level of the quartz-halogen light source in this part of the spectrum. The peak wavelength shift is about 23 nm / mm along the gradient axis and perpendicularly the shift is about 1.10^{-4} of the reference wavelength per millimetre. The mapping of the component allows drawing the peak-wavelength shift over the square of 14*14 mm, as shown in Fig.5.

To characterize the sample FF_FP, the CCD-based set-up has been configured to have a spatial resolution of 40µm (pixel size 17µm, optics magnification 0.423) in order to cover the entire filter surface (20 x 20 mm^2). The spectral resolution was set to 1nm (scan step 1nm, band width 1nm) covering the spectral range from 400nm to 900nm. For each CCD frame, about $256 \cdot 10^5$ samples (pixels) are collected and a set of 500 frames is acquired in about two hours. The transmittance is obtained comparing the signal, given by the same stimuli, of a bare substrate tested under the same conditions. Figure 6.1 shows the filter image when illuminated at 550 nm, while Fig. 6.2 is the profile of the same image along the spectral direction (thickness variation direction) for a point chosen in the middle of the distance for the constant thickness direction.

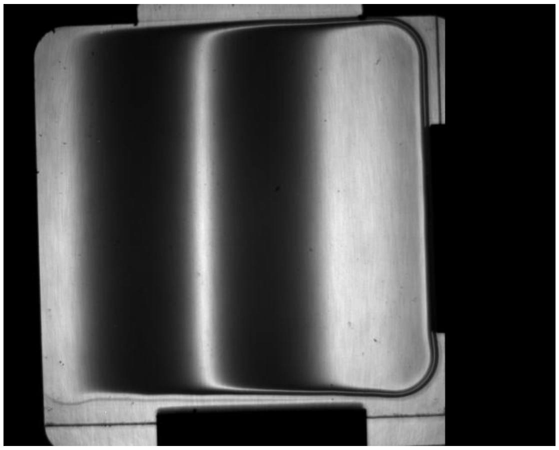


Figure 6. 1 FF_FP image at λ=550nm

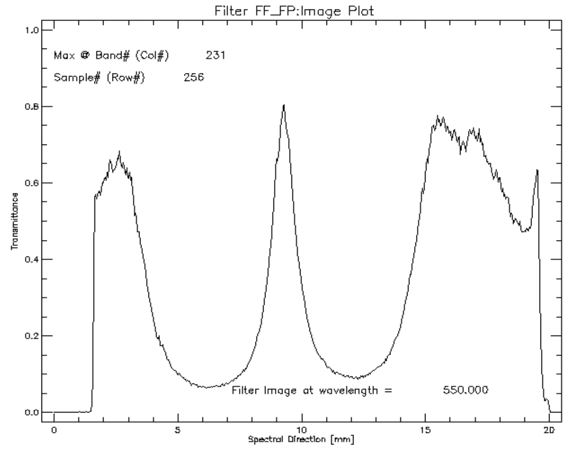


Figure 6.2 Transmittance profile along spectral direction at filter centre for the image at λ=550nm

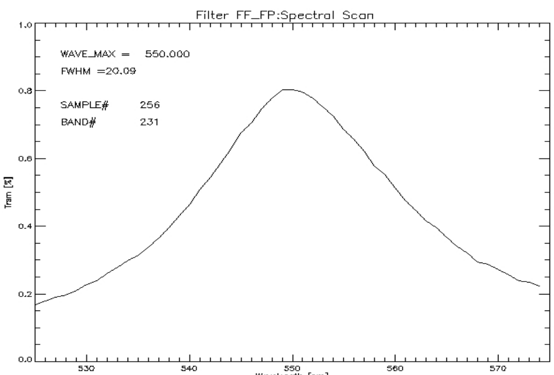


Figure 6.3 FF_FP spectral scan around 550nm

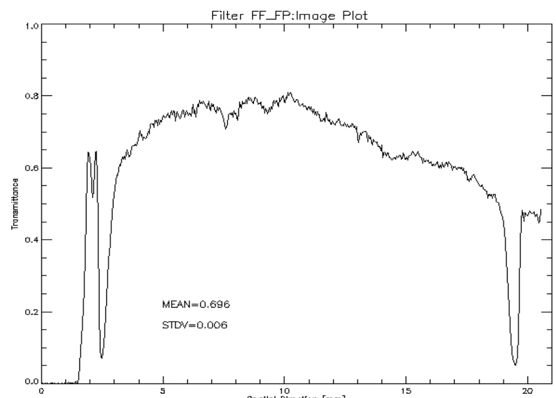


Figure 6.4 FF_FP spatial profile Band#231

Two examples of additional high resolution information available from the second setup measurement are given in Figs.6.3 and 6.4. The spectral scan at a given sample point (Fig.6.3) allows estimation of the transmittance peak parameters, such as peak height and its shape and FWHM, while the spatial profile (Fig.6.4) of a sample is determined at each sample line corresponding to the CCD pixel string.

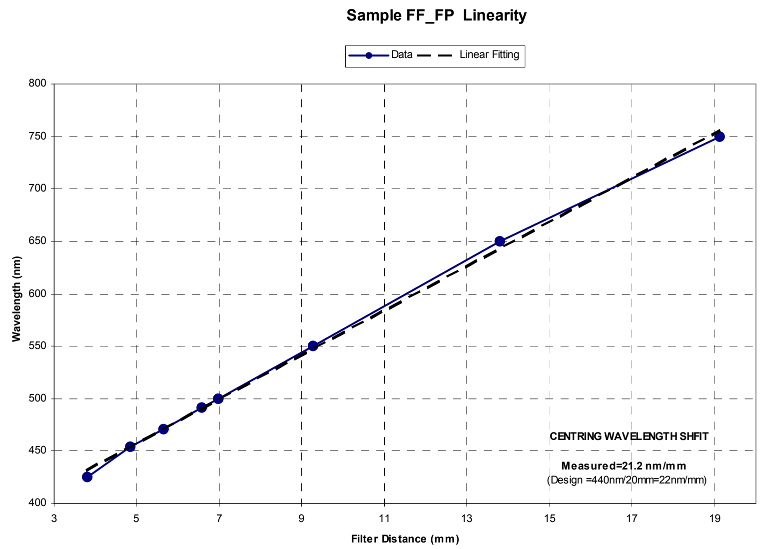


Figure 7. FF_FP peak transmittance wavelength shift, measured with the CCD-based setup: the measurement data (solid line) and its linear fitting (dashed line)

Evaluating the slope of the peak transmittance versus wavelength, Fig.7, the centring wavelength shift of 21.2 nm / mm along the gradient axis was estimated, that corresponds to the value found with the first set-up. The found value is close to the theoretical one (22 nm/mm).

The mirror G5TS37 spectral behaviour for the reference wavelength 590nm (thickest part of the coating) is given in Fig.8. The minimum transmittance position shift along the direction of the coating thickness variation mapped with the first setup is represented in Fig.9. From the last figure a wavelength gradient of about 35nm/mm can be estimated that is in good correspondence with the theoretical value and with the result obtained with the second setup.

Finally, two examples of the measurement with the CCD based setup for the sample G5TS37 are shown in Figs.10.1 and 10.2. First is the sample image when illuminated with at a wavelength of 450nm, while the second is the transmittance profile at the same wavelength.

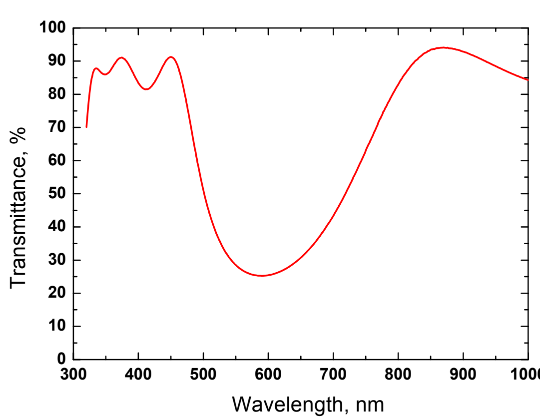


Figure 8. Sample G5TS37: transmittance measured at the point of the maximum coating thickness

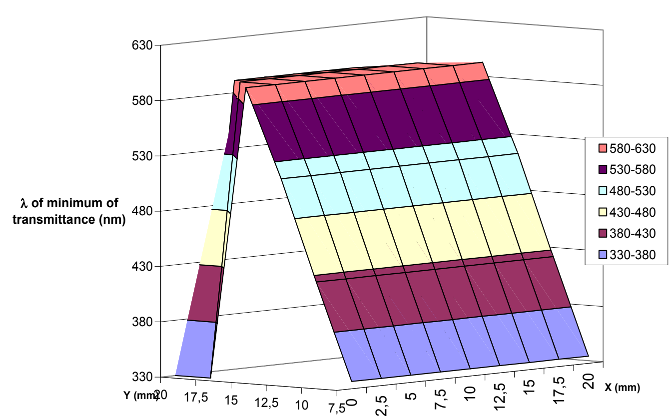


Figure 9. Mapping of the spectral shift of the wavelength of the minimum transmittance of G5TS37 obtained with the first set-up

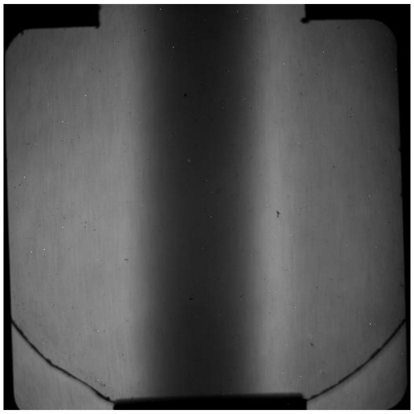


Figure 10.1 G5TS37 image at λ=450nm

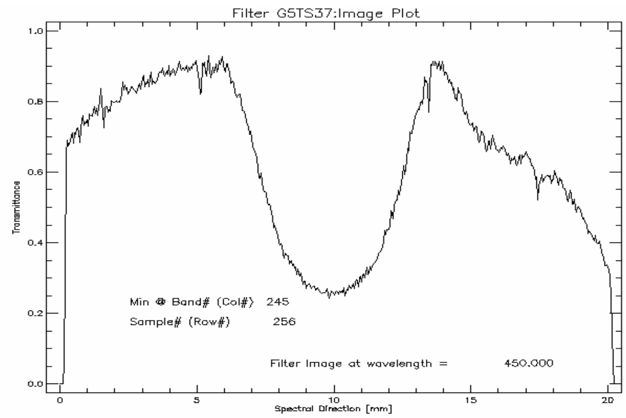


Figure 10.2 Transmittance profile along spectral direction at filter centre for the image at λ=450nm

CONCLUSIONS

Here we present two different instruments constructed for transmittance and reflectance measurement of spatially non-uniform coatings. Different spectral and spatial resolution of these setups provided similar results for two linearly variable coatings that confirms high reliability and accuracy of both types of the measurement.

REFERENCES

[1] D. Morelli, *Interference Filter Handbook*, (OCLI, California, 1998), www.ocli.com

[2] L. Abel-Tiberini, F.Lemarquis and M.Lequime, "Dedicated spectrophotometer for localized transmittance and reflectance measurements", to be published in Applied Optics 2005