

High dynamic broadband measurement of the spectral transmittance of spatially variable optical filters

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ABSTRACT

Earth and planetary observation systems often rely on multispectral and hyperspectral imaging where spatially variable optical filters offer compact, lightweight solutions. In this context, it becomes essential to characterize the optical properties of such filters. This paper presents Micro-SALSA, an instrument designed to measure the local transmittance of spatially variable filters with high dynamic range and spectral resolution. We present transmission spectra of a linear variable filter of high gradient, which has been enabled by the 25 μm spatial resolution and the dynamic range of at least 8 decades over the 400-1700 nm spectral range of our instrument.

Keywords: Optical metrology, Spatially variable filters, Spectral transmission analysis

1. INTRODUCTION

Spectral imaging is widely used for space-based observation, including Earth observation and planetary science. Hyperspectral instruments can provide detailed information on the composition and state of the observed surfaces.^{1,2} Spatially variable optical filters are particularly attractive for these applications as they offer a compact and lightweight solution for spectral imaging, without requiring moving optical components.

The characterization of such filters requires resolving their spectral response at different positions across the filter. This is particularly challenging when the spectral response varies rapidly with position, as in the case of butcher-block filters with narrow stripes or linear variable filters with high spectral gradients. A high spatial resolution is then required to measure the local response, while a high spectral resolution is necessary to accurately resolve the transmission bands. The measurement of the rejection regions also requires a high dynamic range.

We present the Micro-SALSA instrument for the measurement of the spectral transmission of spatially variable filters. This instrument is based on existing source and detection modules of SALSA (Spectral and Angular Light Scattering Apparatus), a high dynamic range and high spectral resolution scatterometer developed at the Institut Fresnel.³⁻⁶ These modules provide the high dynamic range and high spectral resolution of the SALSA instrument, while Micro-SALSA adds a dedicated optical system providing the spatial resolution required for the characterization of spatially varying filters.

In this paper we demonstrate the performance of the instrument through the characterization of a linear variable band-pass filter with a gradient of 150 nm/mm. Measurements are performed at different positions along the gradient to follow the displacement of the transmission band and to determine the relative thickness gradient introduced during the fabrication process.

We also present an evolution of the optical system based solely on reflective optics. This new configuration removes the wavelength-dependent focal shift of the previous system and allows measurements over the entire 400–1700 nm spectral range without changing the optical system between the visible and infrared ranges.

2. LOCAL TRANSMISSION MEASUREMENTS ON A LINEARLY VARIABLE FILTER

2.1 Experimental setup

The local transmittance measurement apparatus presented in this paper is based on the existing source and detection modules of SALSA (Spectral and Angular Light Scattering Apparatus) developed at Institut Fresnel for the measurement of scattering with a 13 decades dynamic range and a spectral resolution better than 1 nm.^{3–6} Both properties are prerequisites for the characterization of spatially variable filters. A dedicated opto-mechanical module was developed and integrated with these existing modules to provide the spatial resolution required for localized transmission measurements. The complete apparatus is illustrated in Fig 1.

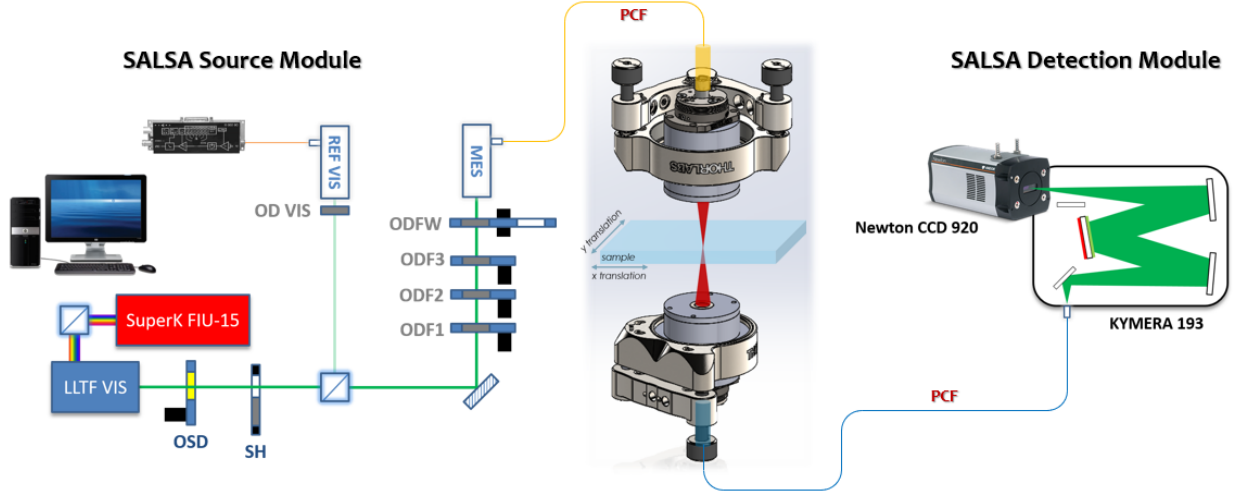


Figure 1. Schematic representation of the measurement apparatus⁷ (SuperK FIU-15: supercontinuum laser source; LLTF VIS: tunable volume hologram filter; OSD: order sorting device; SH: shutter; ODF1, ODF2, ODF3, ODFW, OD VIS: optical densities; REF VIS, MES: reflective collimators for the reference and measurement channels, respectively; PCF: photonic crystal fiber; KYMERA 193: Czerny-Turner monochromator; Newton CCD 920: low-noise scientific-grade CCD camera).

The supercontinuum laser source combined with the two tunable filters allows for a spectral measurement range from 400 to 1700 nm. Several removable optical densities allow the optical power to be adapted to the transmission level of the sample, avoiding detector saturation and ensuring a high dynamic range. The measurement light is guided through a Photonic Crystal Fiber to the optical system, ensuring a single-mode illumination beam across the available wavelength range. The output of the fiber is imaged onto the sample plane with a magnification of 3 using a set of two achromatic doublets.

The receiving optical system is identical and the beam is filtered in the detection module which consists of a Czerny-Turner monochromator and scientific-grade camera. The local transmittance is obtained by comparing the signal measured through the sample with a reference measurement acquired without the sample in the source module. By translating the sample with a motorized microscope stage, a series of local transmission can therefore be recorded, allowing the spectral response of the filter to be mapped.

The instrument has already demonstrated its capabilities in the visible range with measurements showing a dynamic range up to 10 decades, a spectral resolution below 1 nm and a spatial resolution of 25 μm .⁷ The present work extends these measurements to the near-infrared range and demonstrates the capabilities of Micro-SALSA on a challenging linear variable filter with a high spectral gradient.

2.2 Characterization of a linear variable filter

The filter under study is a linear variable band-pass filter designed and fabricated by the Optical Coatings Group in Institut Fresnel. As illustrated in Fig. 2(A), its structure consists of 64 layers on one side of the substrate and 86 layers on the other, with a thickness gradient applied to both stacks. The design targets a band-pass response centered at 1 μm , resulting in a spectral gradient of 150 nm/mm across the filter.

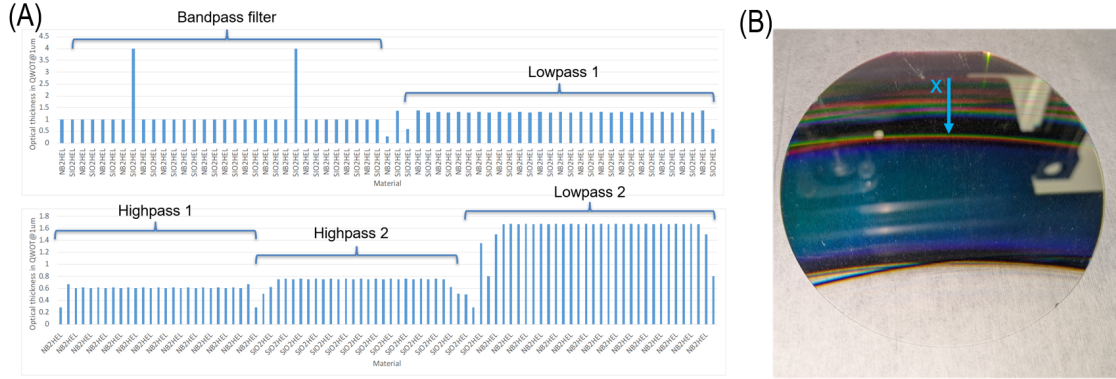


Figure 2. Description of the linear variable filter under study: (A) Formula of both sides of the filter and (B) Picture of the filter with the gradient located by the x axis

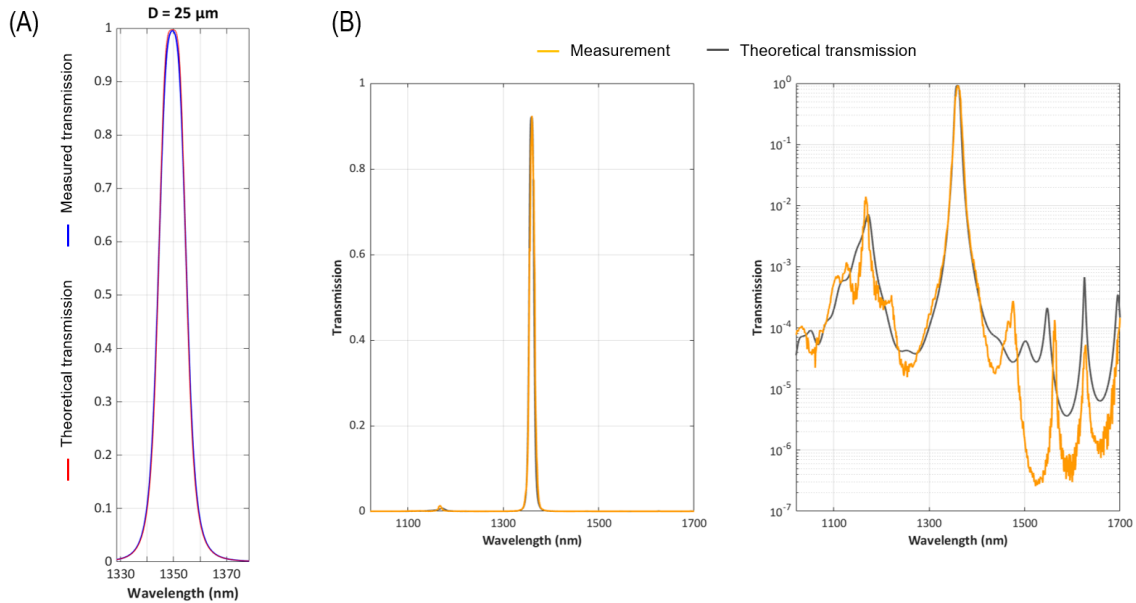


Figure 3. Comparison between the theoretical transmission of the linear variable filter and the expected and measured instrument response: (A) theoretical filter transmission compared with the theoretical measurement limit of the instrument and (B) measured transmission spectrum compared with the theoretical spectrum of the filter.

To quantify the impact of the spatial resolution of the instrument on the characterization of this specific filter, we first calculated the theoretical transmission of the filter at 1350 nm and compared it with the transmission expected when measuring the filter with our setup. We considered a beam diameter of 25 μm , as shown in Fig. 3(A). The two results show a similarity of 98.8%, demonstrating that the spatial resolution of the instrument has a limited impact on the measurement of this filter.

To further validate the measurement, we then performed a spectral transmission measurement on the sample

and compared the measured spectrum with the theoretical transmission spectrum. The results are shown in Fig. 3(B) and illustrate a good agreement between the two spectra, particularly for the main transmission peak. The discrepancies in the rejection range observed at longer wavelengths are believed to result from manufacturing variations.

We then performed spectral transmission measurements at different positions along the gradient and the results are presented in Fig.4.

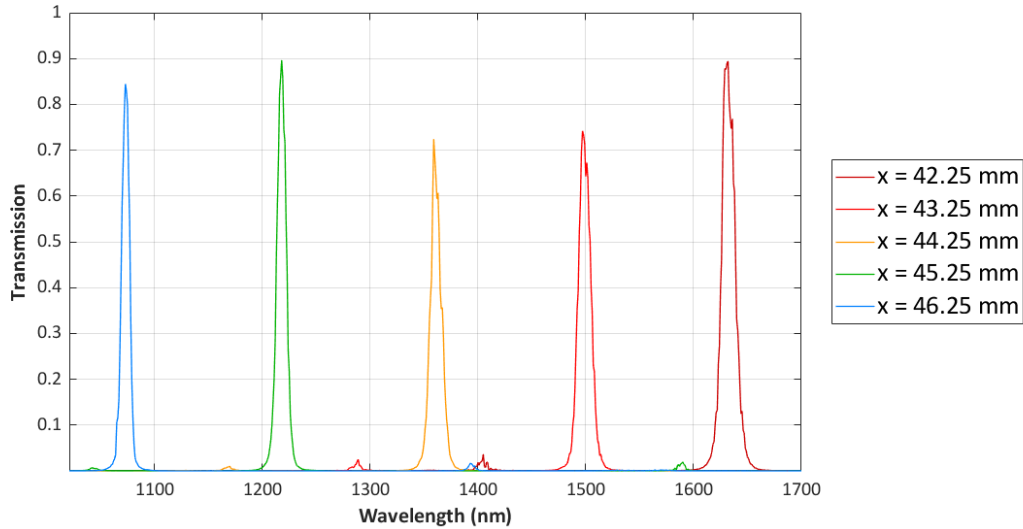


Figure 4. Measured transmission spectra at different positions along the gradient of the filter. The spectra were acquired every 1 mm, with a 1 nm spectral resolution.

The spectra were measured every millimeter and show the displacement of the whole transmission spectrum along the gradient, with the transmission peak shifting towards shorter wavelengths as the position increases. The narrow transmission band remains resolved at all positions, illustrating the ability of the apparatus to follow the spectral variation of the filter with a high spatial resolution.

The measurements are obtained by comparing the spectrum measured through the coated sample with a reference spectrum measured on an uncoated substrate. This allows us to decouple the effects of the illumination beam displacement on the sample and account for the small wavelength-dependent displacement of the focal plane of the optics.

We observe that the gradient is not constant over the spectral range. This is explained by the fact that the gradient is introduced through the thickness variation of the coating. From the positions of the peaks in the spectra, we can deduce a relative thickness gradient of 14%/mm applied to the layers during the fabrication process.

The measurements presented above demonstrate the ability of the instrument to characterize spatially variable filters with high spatial and spectral resolution. However, the use of refractive optics in the current configuration introduces a wavelength-dependent displacement of the focal plane and requires the use of two distinct optical systems, one for the visible range and one for the infrared range.

To overcome those limitations and further improve the versatility of the instrument, a new optical system based on reflective optics was developed. This evolution aims to maintain the spatial resolution and optical properties of the existing system while providing a wavelength-independent imaging system and enabling the use of a single optical assembly over the entire spectral range.

3. EVOLUTIONS OF THE INSTRUMENT

The new optical system mentioned above is presented in this section and illustrated in Fig. 5.

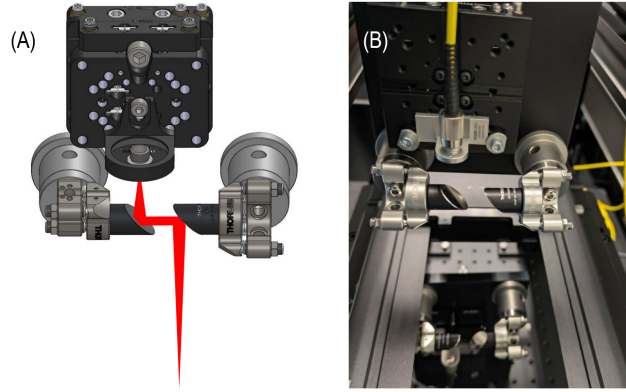


Figure 5. New optical system using only reflective optics: (A) a CAO scheme of the assembly and (B) a picture of the system.

Two off-axis parabolic mirrors allow to image the fiber output on the sample plane with the same magnification 3 as in the previous optical system. The optical properties of the system are maintained, while the use of reflective optics eliminates the wavelength dependence of the focal plane and enables operation over the entire available spectral range, from 400 to 1700 nm. This allows us to perform spectral transmission measurements over the full spectral range on a sample without changing optical system.

A first full range spectrum was acquired on the same linear variable filter and the result is shown in Fig. 6.

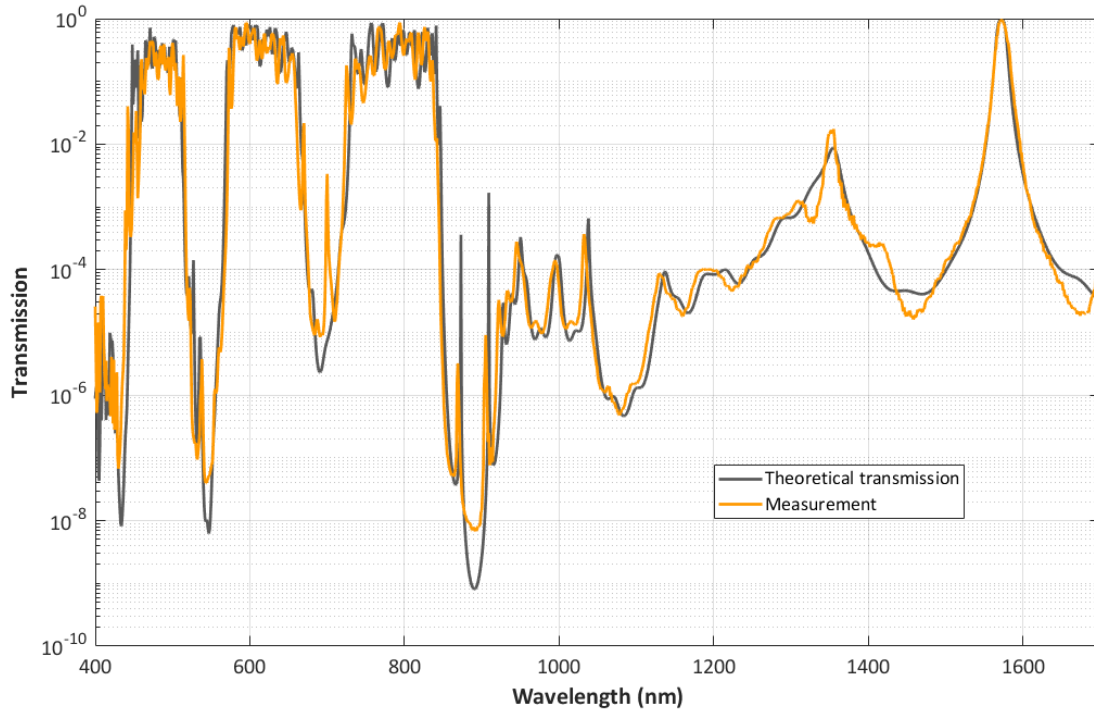


Figure 6. Spectral transmission measurement on the linear variable filter performed with the new optical system compared to the theoretical transmission spectrum

The measured spectrum shows a good agreement with the theoretical transmission over the entire spectral range, from 400 to 1700 nm. The main spectral features of the filter are well reproduced, including the transmission bands and the rejection regions. This measurement demonstrates the ability of the new optical system to perform continuous spectral transmission measurements on the entire spectral range without changing the optical configuration between the visible and infrared ranges.

4. CONCLUSION

We have demonstrated the capabilities of the Micro-SALSA instrument for the measurement of the spectral transmittance of spatially variable optical filters. We performed spectral measurements on a linear variable filter with a gradient of 150 nm/mm. We also presented a new version with a 25 μm spatial resolution and a dynamic range higher than 10 decades of the optical system of Micro-SALSA, allowing for measurements over the entire spectral range from 400 to 1700 nm. Based on a purely reflective optical system, we eliminate the wavelength-dependent focal shift and remove the need to change the optical system between the visible and infrared ranges.

FUNDING AND ACKNOWLEDGMENTS

This work is funded by the French National Space Center (CNES) and the French National Research Agency / Agence Nationale de la Recherche by the funding of X-LOSM project # ANR-23-CE08-0027.

Micro-SALSA is now part of the DIFFUSIF platform (<https://fresnel.fr/diffusif>) as a new instrument to mapping the local transmittance of butcher block filters with high dynamic range.

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