In-band measurement of the transmitted wavefront error in coated bandpass filters

A newly developed system overcomes the limitations of previous measurements.

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As a manufacturer of optical filters, Edmund Optics is constantly facing new challenges, which cannot always be overcome with commercially available solutions, for example in the field of metrology. It is often up to the user of metrology systems, especially in optical manufacturing, to rely on available systems and adapt them to the desired task. In the following, we describe how we worked out our own solution for measuring the transmitted wavefront of optical filters by adapting a commercial Optocraft system to our requirements.

The transmitted wavefront error (TWE) is a relevant quality feature for flat optics, as the performance of an optical system is determined by the contributions of the individual components in the beam path, which then add up to the imaging error of the overall system. This also applies to coated filters, where broadband blocking presents an additional challenge: Optical filters are designed to isolate a specific spectral band, usually in the range of 5 to 50 nm for bandpass filters. Light outside this band, but within the detection range of the sensor in use, is blocked in order to optimise the signal-to-noise ratio. Most applications use silicon-based sensors so that the blocking range is approximately 300 to 1000 nm.

Modern sputtering technologies and optical monitoring systems as used by Edmund Optics allow to achieve relative attenuations of more than 10^6. The surface form error is commonly tested with interferometers which rely on coherent light and therefore operate in a narrow band – usually at 632.8 nm. Only in rare cases, the transmission band of a filter will coincide with the measurement wavelength of the metrology and outside of the transmission band, the extinction is at least 10^{-4}. Thus, the signal becomes too small for a meaningful measurement due to the high blocking values and the transmitted wavefront error of optical filters cannot be reliably measured with such a system.

Search for a suitable system

Edmund Optics started the search for a suitable inspection system by compiling its requirements. In addition to the defined specifications, there are also general requirements for metrology systems used in production. These include a small footprint and robustness as well as somewhat conflicting demands on the software. On the one hand, metrology engineers want to implement various measurement routines and thus need high flexibility and a wide range of functions. On the other hand, operators prefer a simple, user-friendly interface limited to the most necessary options.

As a result of initial comparative measurements and discussions, we chose the Shack-Hartmann system by Optocraft GmbH. The Shack-Hartmann wavefront sensor is based on a geometric-optical method: the wavefront is reconstructed from a single camera image. This enables evaluation rates of several Hertz and provides a high intrinsic measurement stability. Optocraft‘s SHSLab wavefront sensors are characterized by an excellent basic accuracy of a

Overview of system requirements

Requirement	Symbol	Value
Radius of curvature of test specimen	R	∞
Free aperture of test specimen	CA	5 – 50 mm
Thickness of test specimen	t	0.5 – 3.5 mm
Substrate materials		optical glass
Transmission band range	λ	300 – 1200 nm
Blocking band	$\Delta\lambda$	200 – 1200 nm
Transmission %	T	> 95 %
Blocking / Optical density	OD	< 8
Specification limit for wavefront error	max PV	$\lambda / 10$
Measurement uncertainty	max σ	$\lambda / 20$
Max. radius error	max R	$10\,\lambda$
Angle of incidence	θ	0° and 45°

few nanometres RMS and an extremely high dynamic range so that the sensors can also be used to measure highly aberrated wavefronts.

We test optical filters using the SHSInspect RL module in a double pass configuration (**Fig. 1**). The test specimen is illuminated with a collimated wave passing through it and the wave is reflected by a plane mirror and then transmitted a second time through the filter. Thus, the resulting aberrations within the wavefront of the tested filter are amplified by a factor of 2. A Kepler telescope adjusts the pupil diameter of the test specimen to the detection area of the wavefront sensor. In addition, the telescope conjugates the plane of the test specimen with the plane of the microlens array of the wavefront sensor. Consequently, measurement artifacts caused by wavefront propagation between the test specimen plane and the measurement plane are eliminated effectively. The offsets of the measuring system are determined with a blank measurement to subtract them from the measured data of the optical filter. This process yields in combination with the high intrinsic stability of the SHSCam wavefront sensor the required measurement uncertainty of $\lambda/20$ PV.

1 Variable light source
  a Fiber-coupled, laser-pumped white light source
  b Fiber-coupled filter holder
  c Reference light source, LED 530 nm
  d Fiber input (interchangeable between the sources)
2 Optocraft SHSCam
3 SHSInspect RL module
4 Beam expander for 50 mm field of view
5 Interchangeable sample holder
6 Reference mirror, tilt precisely adjustable

Fig. 1 Shop floor implementation of the measuring setup

The Shack-Hartmann software SHSWorks reconstructs the transmitted wavefront and performs the decomposition into individual Zernike coefficients. That way, the system surpasses a mere pass-fail statement by analyzing the aberrations of the test specimen in detail. The wavefront measurement therefore provides extensive data which can be used for process optimization and development.

In addition to these advantages, the modular design allowed the simple integration of a broadband light source. The versatile software further backed the choice of this system.

Working with compromises

However, some compromises were inevitable in the first stage of implementation. First of all, the bandwidth of the system had to be reduced to 400 to 700 nm. Limiting factors were the coatings of the internal optics and the chromatic correction of the imaging systems. Thus, a second system based on the same principle and optimized for the NIR range was part of the plan from the beginning. In addition, the focus was initially placed on larger filters. Optics with a diameter of less than 10 mm are normally used in front of photodiodes instead of image sensors, and therefore do not have to fulfil any special requirements in terms of the transmitted wavefront: We optimized the system for diameters from 12.5 to 50 mm.

In the final setup (**Fig. 1**), the upright housing minimizes space requirements and the two-part door allows access to the sample chamber without exposing the system itself thus minimizing the likelihood of unwanted changes to the setup. The light source is a laser-pumped, phosphorescent white light source. Two blue laser diodes at 450 nm are used as the pump source. The light source is fiber-coupled to facilitate integration and offers very high intensity. This hard criterion ensures the reliable measurement of narrowband filters.

Sample holders were created for the most frequently used sizes at 0° and 45°, respectively. They are easily removed for the loading and snap firmly into the mount at the sample chamber for their repeatable positioning in the beam path. Filter production at Edmund Optics is specialized in customized products which requires adaptable metrology. Therefore, the design of the sample holders focused on simple, cost-effective manufacturability and adaptability, in this case using 3D printing or CNC machining.

Verification measurements

In a first step, uncoated test glasses were evaluated to verify the accuracy of the measurement. Reference measurements were based on interferometers from Zygo and Interoptics at our production sites in Mainz and Japan. The test glasses are from the Edmund Optics catalog: item #43-893 with a transmitted wavefront error below $\lambda/4$.

The results measured with illumination wavelengths of 530 and 633 nm are stable and consistent. A comparison with the interferometer data shows that the measured PV values tend to agree better than the irregularity values. Since the latter use an analytical reconstruction of the measurement data, slight differences in the algorithms of the respective manufacturer's software might explain this deviation. An analysis of the raw data with the same software might prove this assumption. As the deviations were within an acceptable range, no further investigation was carried out.

Application to optical filters

In the next step, a multiband filter from the Edmund Optics product line was measured with transmission bands at 457 nm, 530 nm, and 628 nm. Its transmitted wavefront error is not explicitly specified. However, the wafer substrates used in production do not exceed an error of $\lambda/4$ RMS in transmission over the entire diameter before coating. The three design wavelengths are emission lines of different fluorophores since the filter is designed to be used in the imaging path of a fluorescence setup. Therefore, a low wavefront benefits the application.

The measurement was carried out in the individual bands: 457 nm with the broadband source and pre-filtering at 450 nm, 530 nm with the supplied LED source, and 628 nm with the broadband source and pre-filtering at 633 nm. In addition, a synchronous measurement of the total wavefront used the broadband source and a second multiband filter of the same type.

Measuring the individual bands resulted in some learning effects. In the red spectral range, the measurement proceeded without difficulty and convincing results (**Fig. 2**). The light of the source was filtered to 633 nm with a half-width of only 5 nm thus being exactly within the specified transmission band.

The measurement with 450 nm revealed a peculiarity of the selected light source. The laser diodes serving as pump sources emit in the transmission range of the filter used in the beam path for

Measurement data for item #43-893

	Transmitted wavefront error			
	Measurement 530 nm, LED		Measurement 633 nm, white light + filter	
Measurement #	**PV, λ @ 633 nm**	**IRR, λ @ 633 nm**	**PV, λ @ 633 nm**	**IRR, λ @ 633 nm**
Average of five measurements	0.203	0.190	0.204	0.198
Standard deviation	0.009	0.004	0.009	0.012
Difference to the reference measurement	0.001	0.022	0.002	0.013

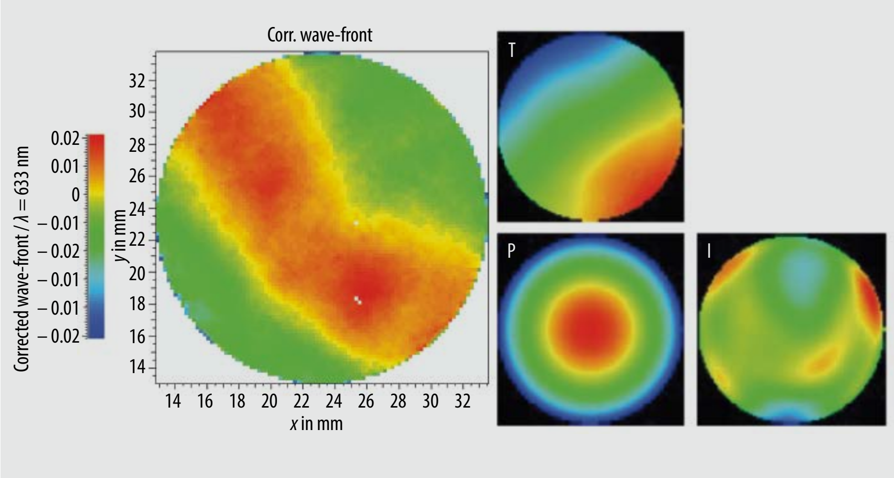

Fig. 2 Measurement data at 633 nm corrected for tilt (left) and analytical reconstruction of the measurement including tilt (T), power (P), and irregularity (I)

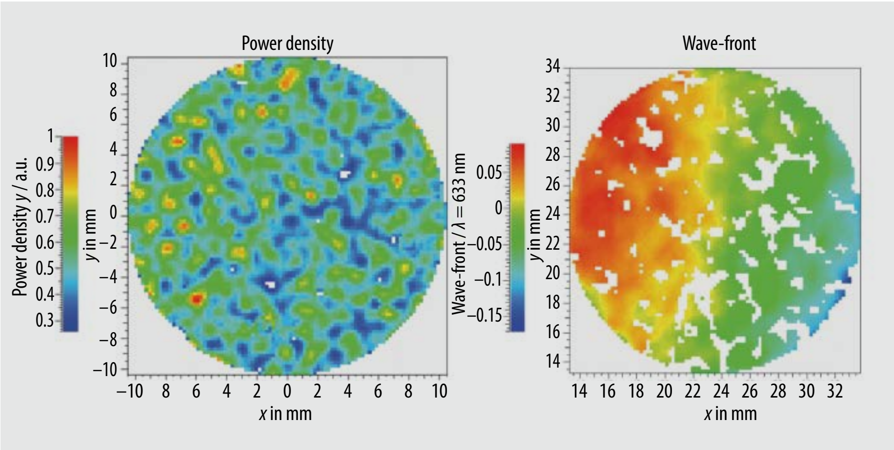

Fig. 3 Measurement at 450 nm: The evaluation of the intensity on the sensor shows clear hot-spots and strong fluctuation (left). The resulting error map with the sensor values set to default reflects this behaviour (right).

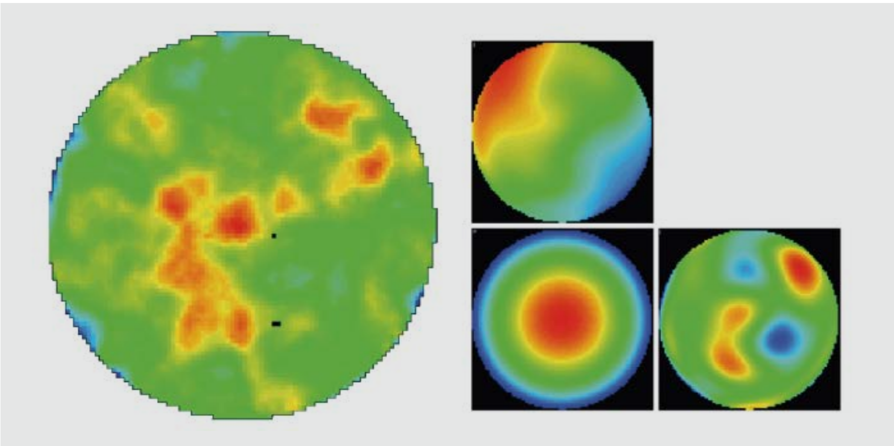

Fig. 4 Measurement data at 450 nm with adjusted sensor threshold values and corrected for tilt (left) and the reconstructed error maps (right)

the illumination. Therefore, coherent laser light dominates the illumination resulting in a notable speckle pattern when the light is emitted from the fiber. The highly non-uniform illumination on the sensor and the fragmented surface maps (**Fig. 3**) were only manageable by the software: The experts from Optocraft manually optimized the sensor threshold and significantly improved the result (**Fig. 4**). In addition, the convenient file format of the raw data allowed a retrospective adaptation of these parameters. The Zernike reconstruction of the data in accordance with ISO 10110 further helps to smoothen out the noise. The data determined for power and irregularity does not deviate significantly from the other wavelengths. Nevertheless, a systematic solution is planned in the medium term to enable reliable measurements in the blue spectral range as well.

As the bandwidth of the LED was wider than the transmission range of the filter, the data for the 530 nm band showed a ghost image due to a superposition of reflected and transmitted signals. A tilt angle of a few degrees, which was not checked more precisely, avoided this issue.

Convincing results

The measurement with the multi-band filter showed isolated artifacts – similar to the 450 nm measurement, but to a much lesser extent. On the one hand, the superposition with the other wavelengths produced a more homogeneous intensity distribution. On the other hand, the shifted transmission band in the blue wavelength range blocks more light from the pump laser.

Despite the minor difficulties, the measurements yielded very convincing values: The complex combination of the multi-band coating with blocking via OD6 results in high stresses within the coating system which transfer to the substrate. Nevertheless, the wavefront error in transmission is below $\lambda/10$ and the deviations of the different measurement series are within the system accuracy range. The measurements reliably characterize the filter regardless of the wavelength in use and the quality of the transmitted wavefront also satisfies high demands in imaging systems.

After the completion of the measurements, the system was put into operation at the Edmund Optics manufacturing plant in Yuzawa City, Akita prefecture, Japan.

Outlook and lessons learned

Future improvements will tackle mostly two points. As described, the laser-pumped illumination causes speckle formation around 450 nm. In addition, it does not fully utilize the possible spectral range of the wavefront sensor because the emission spectrum in the short-wave range ends with the pump laser. The course of the test measurements revealed that the light intensity is less of a problem than anticipated when measuring narrow filters. Even for filters with a transmission band of only 5 nm width, the intensity of the light source must be reduced significantly to allow reasonable exposure times for the sensor. A light source with a slightly broader bandwidth and lower intensity but without a coherent pump source would further improve the functionality of the system. Its retrofit is planned in the medium term. In the short term, an additional notch filter will help to suppress the laser.

In addition, another beam path for measuring the reflected wavefront at an angle of incidence of 45° should be implemented in order to fully measure products such as dichroic beam combiners: their imaging errors are specified both in transmission and reflection.

In conclusion, implementing the measurement system for the transmitted wavefront error of optical filters was successful. The setup relies on the strong and proven basis of the Optocraft SHSCam and SHSInspect RL module. It meets the key requirements for characterizing the transmitted wavefront of optical filters and enhances Edmund Optics‘ manufacturing capabilities in the field of optical filters for imaging applications, like fluorescence microscopy relying on low wavefront distortion.

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Overview of multi-band filter measurement data

Measuring wavelength	TWE (λ @ 633 nm)		
	PV	Power	IRR
450 nm	0.17	0.02	0.07
530 nm	0.10	0.02	0.06
633 nm	0.13	0.05	0.08
Multiband	0.12	0.05	0.05