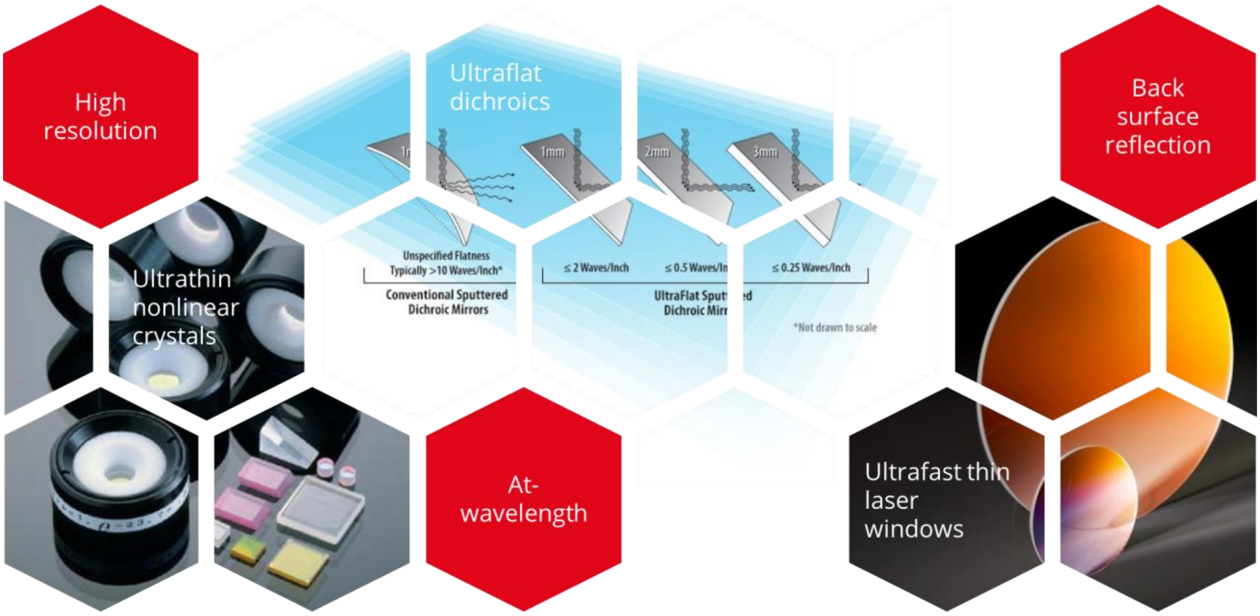

APPLICATION NOTE

OPTICAL METROLOGY OF MULTIPLE FLAT SURFACES USING SHACK-HARTMANN TECHNOLOGY

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Summary

The Shack-Hartmann wavefront sensor has established itself as an optical metrology tool for its ease of use, very high dynamic range, achromatic nature and versatility. A new implementation has been recently proposed to characterize multiple surfaces of a single sample, taking advantage of its ability to measure a combination of several wavefronts without the raw acquired signal being compromised, as no interference is produced. Better yet, it accommodates sources across all wavelengths, and has been upgraded to significantly improve its resolution!

INTRODUCTION

Non-contact metrology of optical components is paramount, whether during the manufacturing process, to optimize it, or once the part is completed, to validate its optical quality and specifications. The need concerns both manufacturers and integrators or users of these components. Among these, parts with parallel surfaces require a particular effort in the implementation of their inspection, both due to their geometry -such as windows, wafers, protective screens- or their spectral properties -crystals, filters, dichroics, beamsplitters and any substrate that has received an anti-reflection or reflective coating-. The parallelism of parallel surfaces makes it indeed complicated to separate the signal coming from one surface from the other, creating artifacts that limit the precision of metrology solutions. For instance, in the case of a Fizeau interferometer, a 3-wave interference pattern forms which hinders data reconstruction. The coatings applied, or the materials used, can in turn make systematic metrology at the HeNe laser wavelength complicated or impossible. For example, measuring the surface form of a laser optic with a reflective coating at 800 nm becomes problematic when it is transparent at 632.8 nm!

Solutions of varying degrees of practicality and cost have indeed been developed [1]. Thus, many users have applied a coating, almost a secret sauce, to the rear surface of their samples to be tested, to prevent the reflection from the rear surface from disturbing their measurements. Nevertheless, this means preparing the part, and therefore cleaning it afterwards, which strongly impacts the time dedicated to the metrology of the part. Furthermore, the coating can alter the shape of the part and introduce measurement errors, especially if it is thin, and represent a handling risk for the part. Other approaches work on the properties of the source, such as its coherence length, to select the characterized surfaces. They represent a real additional financial and setting up cost.

Imagine Optic, drawing on its expertise in wavefront measurement using Shack-Hartmann technology, has patented an approach, called POP, which takes advantage of the robustness of the technology. It allows easy and straightforward testing of screens and windows, filters and dichroic filters, or laser crystals. It is compatible with all sample thicknesses and adapts to the spectral properties of surface coatings to qualify optics either in transmission or in reflection. These features are made possible by the combined use of common low coherence length light sources, at any wavelength, and a high-resolution Shack-Hartmann wavefront sensor.

EXPLOITING THE MEASUREMENT OF MULTIPLE AVERAGED (COMBINED) WAVEFRONTS

The method, which applies to optical samples partially transparent at the test wavelength, is described for a sample with flat and parallel surfaces. It is illuminated by an incident beam of low temporal coherence, and the beams reflected by each surface of the sample, as well as the transmitted beam, are directed towards a Shack-Hartmann wavefront sensor by means of an optical system that adapts the diameter of the analysis pupil (figure 1 left).

The principle of the method is simple: the realization of two measurements (M_1 and M_2) linking two unknowns to be determined -α the deformation of surface A of the sample and β the deformation of the second surface B- allows their determination by solving a system of linear equations. The Shack-Hartmann wavefront sensor is in this case a tool that adapts perfectly to this approach as it can measure the combination of several contributions without them destructively interfering with each other, using a low temporal coherence source. Each contribution simply needs to be weighted by its relative intensity.

The method therefore consists of first performing the measurement (M_1) of the average wavefront corresponding to the deformation produced in reflection by the two surfaces A and B of the sample:

$$M_1 = \frac{[2\alpha(R_A + R'_B) - 2R'_B n(\alpha - \beta)]}{R_A + R'_B}$$

where n is the refractive index of the sample. Each contribution is weighted by the coefficients R_A for surface A and $R_B' = R_B(1-R_A)^2T^2$ for surface B, with R_A and R_B the reflectances of surfaces A and B respectively, and T the transmission of the sample.

Then, the method proposes the acquisition of the wavefront corresponding to the deformation produced in transmission through both surfaces of the sample (M_2):

$$M_2 = (n-1)(\alpha - \beta)$$

The surface form errors can then be derived from the two measurements performed (figure 1 right):

$$\alpha = \frac{M_1}{2} - \left(\frac{nR'_B M_2}{2(n-1)(R_A + R'_B)}\right)$$

$$\beta = \alpha + \left(\frac{M_2}{2(n-1)}\right)$$

The method presents several advantages:

It is not necessary to handle and flip the sample to access the properties of each surface, as required by classical optical measurement in reflection, or by contact measurement. It is also not necessary to prepare the sample, which minimizes the impact of metrology in the manufacturing process or final quality control, with a complete test cycle in less than 1 minute.

The technique works at any wavelength: it thus adapts perfectly to the spectral constraints imposed by the designs and the parts to be inspected, due to the properties of the materials or their optical coating, and parts can therefore be qualified after coating as well, meeting the growing requirements of optical applications.

The technique is compatible with extremely thin samples -a few tens of microns- thanks to the use of low coherence sources, such as SLEDs for example, which are easily available, cost-effective and durable. The periodic maintenance of the source used for metrology is no longer a recurring and costly burden as in the case of solutions based on interferometry and highly stable lasers.

The method also inherits the advantages of Shack-Hartmann technology, and is robust to vibrations. This facilitates its implementation in usually demanding environments, closer to the production line, avoiding the need to move samples to the metrology laboratory with the constraints this implies: impact on yield, risk for optical parts, whether fragile or requiring many manufacturing iterations, or handling inconveniences, such as bulky or extremely heavy parts.

Finally, the technique is compatible with measurements on multiple regions of interest simultaneously, which allows the inspection of assemblies: crystal bundles, parts cemented on the same mount for example, all at the same throughput.

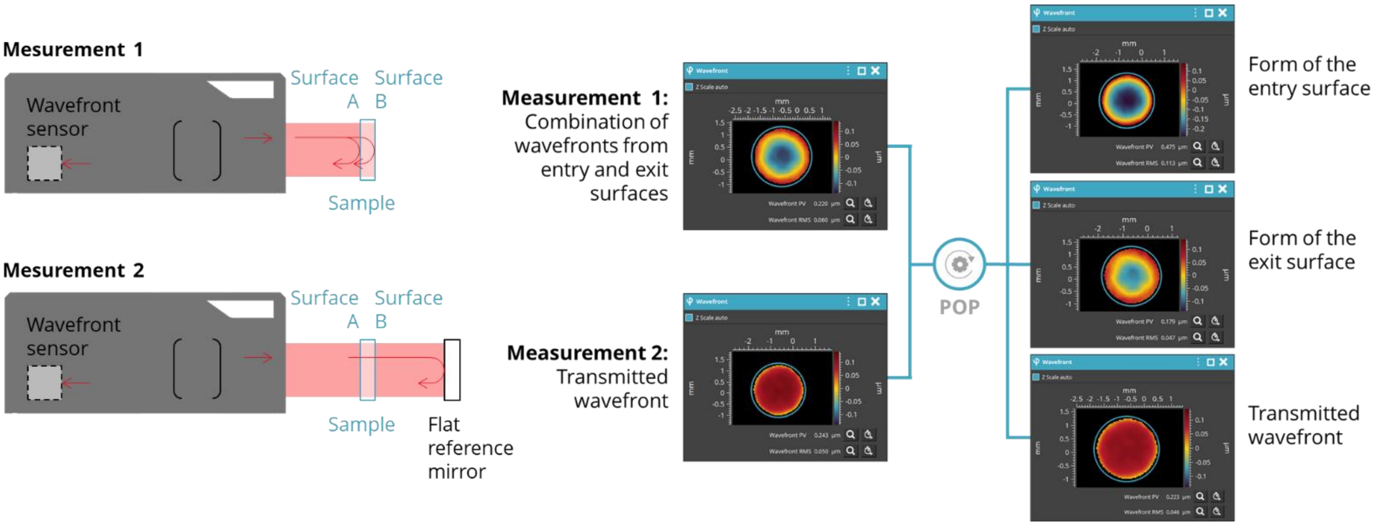


Figure 1. *Left: measurement protocol of the POP method. The sample to be characterized is placed and aligned once in front of an optical system composed of an illumination source and a wavefront sensor operating in double pass. Right: the POP algorithms compute the surface forms of the sample from the average wavefront measurements, and as a bonus, the transmitted wavefront quality.*

DEMONSTRATION AND MEASUREMENT RESULTS

To demonstrate the accuracy of the surface form measurement of an optical sample using the POP method, a 40 mm diameter and 10 mm thickness gauge, whose two surfaces have been coated, was used. The reflectance characteristics of each surface are visible in figure 2. For the wavefront measurement, the MESO$_L$ instrument [2], equipped with 4 sources at wavelengths 405 nm, 520 nm, 635 nm and 850 nm was selected and, among the 5 motorized optical zooms it integrates, set to the 2-inch (50 mm) test beam diameter.

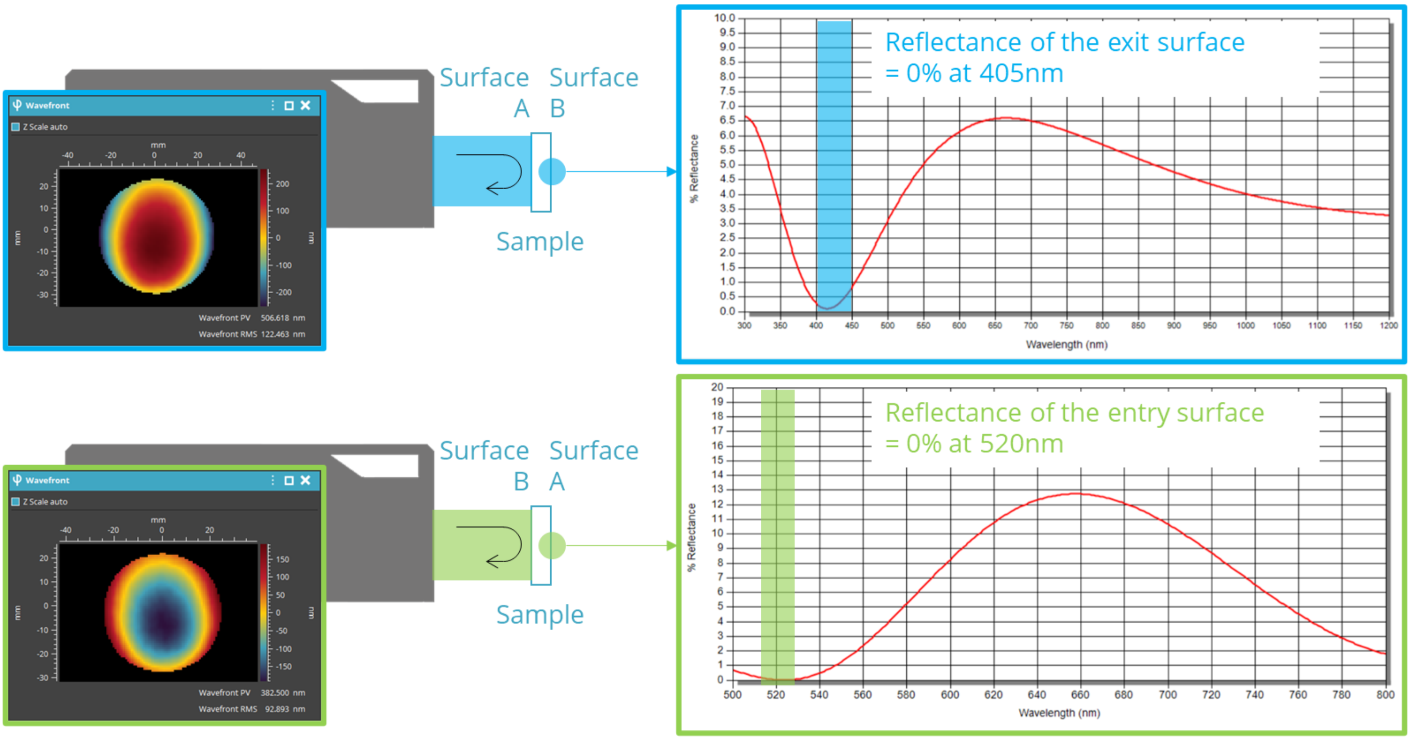
For the measurement of the first surface (A), the gauge is placed in front of the instrument, aligned via the user interface and measured at 405 nm. As the exit surface (B) is coated with an anti-reflection coating at 405 nm, there is no unwanted parasitic signal generated by surface B of the sample that would disturb the measurement. For the measurement of the second surface (B), the gauge is flipped, realigned and measured at 520 nm. As the exit surface of this configuration (A) is coated with an anti-reflection coating at 520 nm, it is again ensured that there is no unwanted parasitic signal that would disturb the measurement. These two measurements, performed in a classical reflection mode, provide a wavefront error reference against which to compare the measurement.

The same gauge is now measured using the POP method. For this, the gauge is placed in front of the instrument and aligned only once: it will not be necessary to flip it to perform the two measurements presented in the previous section: the first corresponding to the combined wavefronts of the two surfaces in reflection, the second corresponding to the transmission measurement of the sample in double pass. The developed algorithms then return the two wavefront error maps of the two surface forms. It is then possible to compare them to the previous measurements obtained in reflection.

The results obtained are summarized in table 1.

	Classical reflection-based measurement	POP method-based measurement
Surface A	122,5 nm RMS	125,7 nm RMS
Surface B	92,9 nm RMS	90,1 nm RMS

It can be observed that the surface form measurements are perfectly consistent: surface A and surface B present the same RMS wavefront errors regardless of the test



Wavefront PV 506.618 nm
Wavefront RMS 122.463 nm

Wavefront PV 382.500 nm
Wavefront RMS 92.893 nm

Figure 2. *Measurement of the surface form in reflection, ensuring the absence of parasitic reflection from the rear surface of the sample through appropriate selection of the test wavelength: top, measurement at 405 nm; bottom, measurement at 520 nm.*

method used, within the margin of error of the instrument used (λ/100 RMS).

Additional results: it can also be noted that measurement accuracy is ensured even though the different measurements were performed at 3 different wavelengths, which also demonstrates the achromaticity of the Shack-Hartmann wavefront sensor. The surface form maps visible in figures 2 or 3 also show that the sample is not perfectly flat. Surface A is slightly convex, and surface B slightly concave.

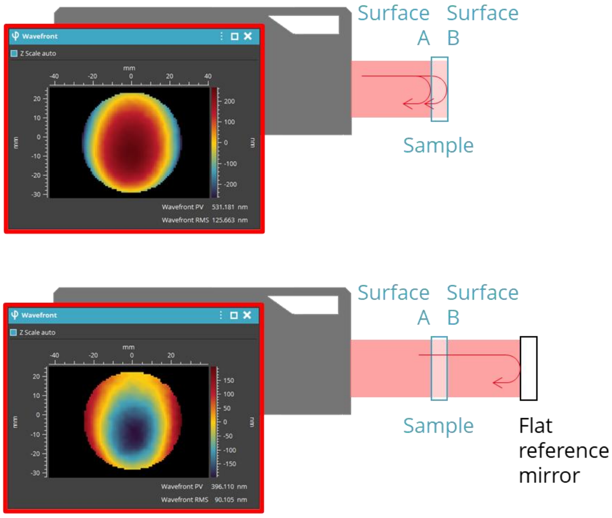


Figure 3. *Measurement of surface form with POP method*

The POP method can also be applied to samples prior to coating, such as large diameter (200 mm) thin substrates (2 mm) visible in figure 4, in order to select the surface of best quality. This surface is the one that will be coated with a reflective coating for high intensity lasers, namely "SURFACE_A" in the presented case. The method allows to minimize the handling of the delicate sample, and to optimize the optical quality of the produced mirrors.

CONCLUSION

The POP method demonstrates that an innovative exploitation of Shack-Hartmann technology allows to efficiently address the challenges of metrology of parallel surface optics. By measuring combined wavefronts without interference using low coherence sources, it enables the simultaneous reconstruction of the surface forms of both sides of a single sample, without preparation or flipping, and at any wavelength.

The experimental results show excellent consistency with reference measurements in reflection, confirming the accuracy and achromaticity of the approach. Beyond metrological performance, the developed method stands out for its speed, environmental robustness and compatibility with demanding industrial environments.

The development prospects concern the extension to large diameter components, and the adaptation of the method to determine the refractive index variation of the sample. POP positions itself as a promising evolution of photonic metrology, suited to the growing demands of modern optical manufacturing.

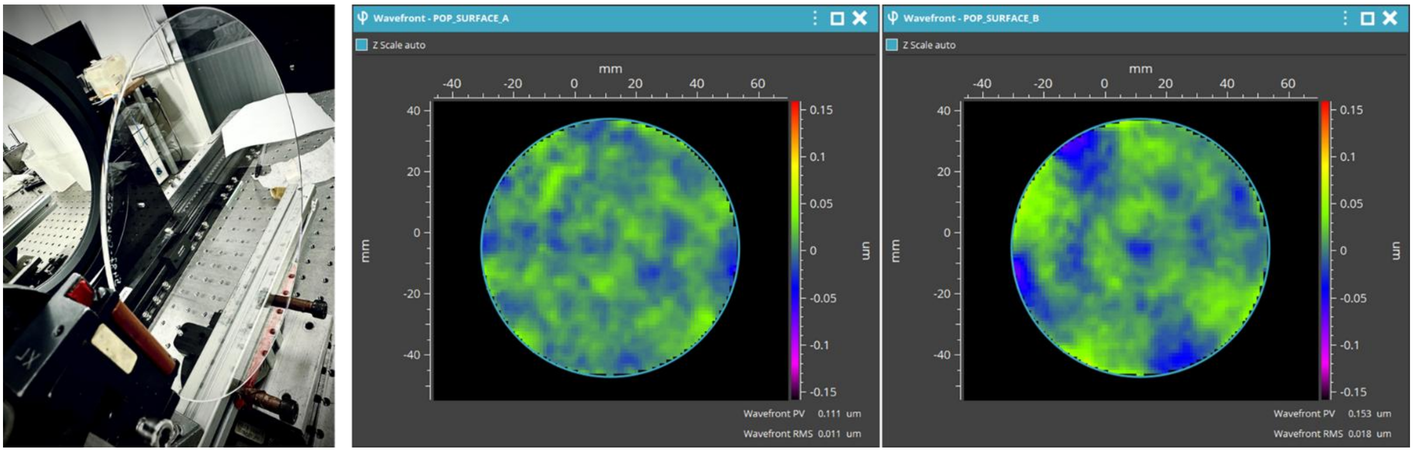


Figure 4. *Left: Large, thin flat windows characterized with the POP method; right: surface forms plotted without curvature (sphere) to select the best surface for coating deposition*

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