D2.4 Process optimized high NA scanning objective

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VERSION HISTORY

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INTRODUCTION

ADALAM Context

Workpackage Context

The main objective of this work package is to design and implement a complete solution for an inline topography measurement and analysis for monitoring before, during and after the laser micro machining. The following approach integrates a high-resolution optical distance measurement system in the beam path of the laser micro machine, enabling an in-line measurement of the current state of the machined micro- and macro-structures directly in machine coordinates. Based on this device an automatic and adaptive process will be enabled. The following solution uses a low coherence spectral interferometer in a Michelson-type set-up, with a measurement path through the scanning optical system and an external reference path.

One of the biggest challenges herewith are the very tight axial and lateral tolerances of the process. Especially the required lateral tolerances under 10 µm demands special developments on the measurement system and on the machine optical system.

Moreover the high shape and feature variation of the workpieces to be manufactured represents a further challenge especially in regards to the numerical aperture of the optical system as well as to the measurement data processing and analysis.

Finally the overall optical effects of the scanning optics (scanning mirror and objective) represent a challenge for the measurement system regarding effects on the optical path, measurement spot diameter, laser and measurement beam coaxiality. Especially the internal dispersion properties of a telecentric scanning lens cause a wavelength and field angle dependent change in the measurement beam's focal length and beam waist diameter. Furthermore the optical path of the measurement beam is distorted by the optical aberration of the optical system. This effect is in addition position dependent, leading to a position dependent optical path.

These effects need to be characterized and compensated in the measurement system unit and integration / coupling unit. The sensing unit will rely heavily on the use of adaptive optical elements. An attractive feature of adaptive optics is that it can alleviate the extreme requirements on the scanning objective and can be tuned to the specific objective used in a setup after a calibration step.
In order to fulfill the main objective and cope with the related challenges four work areas / specific objectives were defined and subdivided on working groups, which are lead and executed by partners regarding their expertise. The work areas / specific objectives are as follows:

- Design and implementation of an **optical high-precision distance measurement system** optimized for the ultra-short pulse (USP) laser characteristics (high power and ultra short pulse duration), machine optical system and process axial and lateral tolerances;
- Concept and design of an optimized **scanning objective** with enhanced numerical aperture and lateral accuracy (reduced laser and measurement spots) as well as reduced focal depth and chromatic aberration regarding the measurement beam wavelength;
- Implementation of an **beam shaping unit** for beam coupling and sensor integration based on adaptive optics;

○ Design and Implementation of an **automatic point cloud analysis software** for feature detection and characterization for the generation of qualified information, which is feed back to the machine for process adaptation and control.

○ Design and implementation of **evaluation and calibration methodology** to ensure high fidelity and reliable data. This work will be done in close collaboration with WP4.

As a second solution to comply in particular with the required lateral resolution, a high numerical aperture (NA) sensing head will be developed and attached to the machine scanning unit not using the optics of the scanning head. The measurement system device will address both sensing paths based on an optical switch (see picture in section 1), being able therefore to measure through the processing optics as well as through the high NA sensing head. This solution has the advantage of offering additional versatility to the machining head when measuring smaller structures, which are not measureable by the main sensing head.

Task Context

In this task a high NA scanning objective has to be developed and manufactured. It addresses two of the previously described work package challenges / objectives related to demands on high lateral resolution for laser and measurement applications (fewer than 10 µm) and high numerical aperture. Furthermore the scanning lens will be designed considering the overall optical aberration effects on the measurement beam, which should be kept minimal. The remaining effects will be compensated using the beam shaping unit, developed in Task 2.5.

The task is divided into 5 steps:
1- Definition of the scanning optical system specifications related to previously specified process and measurement demands and specification;
2- Simulation-aided design of the scanning lens based on Zemax optical design;
3- Mechanical design of the different optical elements of the scanning optical system;
4- Optical grinding, polishing and coating of the scanning optical system;
5- Interferometric test for lenses quality and function supported assembly.

High NA scanning objective

Specifications

General Requirements

The overall optical effects of the scanning optics (scanning mirror and objective) represent a challenge for the measurement system regarding effects on the optical path, measurement spot diameter, laser and measurement beam coaxiality. Especially the internal dispersion properties of a telecentric scanning lens cause a wavelength and field angle dependent change in the measurement beam's focal length and beam waist diameter. Furthermore the optical path of the measurement beam is distorted by the optical aberration of the optical system. This effect is in addition position dependent, leading to a position dependent optical path.

For this reason an optimized scanning objective with enhanced numerical aperture and lateral accuracy (reduced laser and measurement spots) as well as reduced chromatic aberration regarding the measurement beam wavelength has been implemented.

Direct goals to be achieved with this system are:

Enhancement of the lateral accuracy of the integrated measurement system over the complete scanning area

- Minimization of the focal length displacement between measurement and laser beams
- Minimization of the spot displacement between measurement and laser beams
- Maximization of the telecentricity for the measurement beam
- Minimization of the optical path length difference (OPLD) changes within the scanning lens

Specifications 1st generation system

Laser wavelength	1064 nm
Measurement wavelength	close to the laser wavelength to avoid optical aberrations
Measurement range	~ 2 mm (depth of focus)
Measurement resolution	Detection of single pulse removal (depth < 1 µm \ diameter < 100 µm)
Meas. spot displacement	< double of the laser spot diameter
Measurement area	Usage of > 50% of the working field
Spot size deviation	Scanning lens influence on the laser spot dimension < 100%
Lateral accuracy	Less than a laser spot radius

Optical Design

The optical design of the new F-Theta lens has been performed with the simulation software Zemax. In order to create small and precise structures, the design aimed towards a small spot size and thus a high NA. The second challenge was the necessity of a color correction for the measurement beam and the potential use of (ultra) short-pulsed laser. The benefits of such lasers in regards to micro structuring are effects like cold ablation or filament cutting for the creation of deep structures.
For pulse lengths shorter than 1 ps, the laser creates a noticeable spectral band-width, which can have an impact on the spot performance. Thus, an 800 fs Gaussian shaped pulse has a spectral width of approx. 2 nm and a 250 fs pulse a width of almost 7 nm.
Usually, laser lenses are corrected for monochromatic light. The spectral bandwidth of short pulse lasers results in so-called color errors both in and transverse to the propagation direction. The resulting spot will be distorted and blurred, as the laser pulse intensity is spread onto a larger area.

Parameters	
Focal length	100 mm
Laser wavelength	1064 nm
Measurement wavelength	980 nm +/-50 nm
Entrance beam diameter	10 mm ($1/e^2$)
Field size	35 x 35 mm

Table 1: Physical properties of the new scan lens

The new scan lens was designed with the physical parameters in Table 1 and considering to achieve the required accuracy mentioned above, by minimizing all relevant aberrations. The result is a telecentric scan lens that can perform a minimum spot diameter of about 20 µm (see Figure 1) and a good chromatic accuracy (figures 2 and 3).

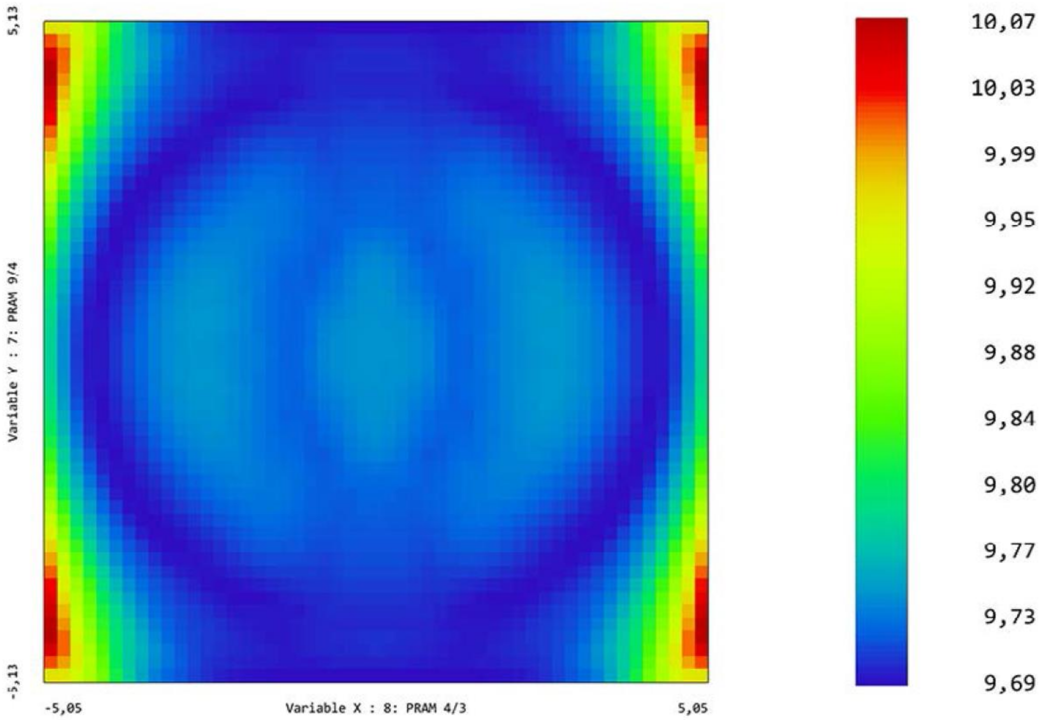

Figure 1: Spot radius in µm over the scan field, clipped at 1/e

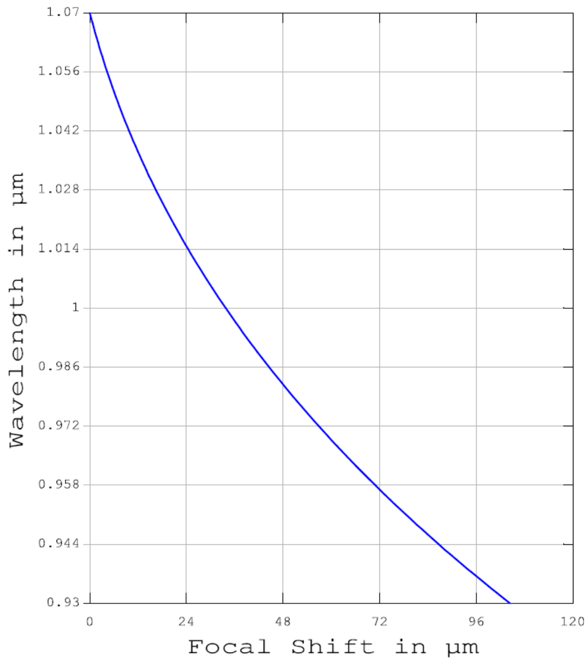

Figure 2: Chromatic focal shift

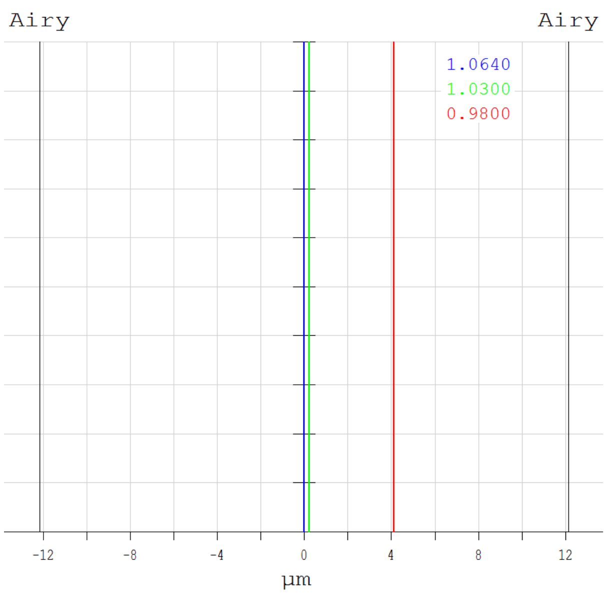

Figure 3: Lateral color error

In comparison to previously tested scan lenses the results according spot size deviation and color errors were very good. Another important criterion is the optical path length difference (OPLD) over the field as well as over all wavelength. The primary effort was spend on optimizing the color correction. This makes it hard to put weight on the optimization of the OPD. Former test showed that the OPD of the previously used lens was good enough for the process. The former lens (S4LFT0080/126 from Sill), is a non-color corrected lens, which is designed for 1064 nm only. For the new optimized scanning lens we were able to keep the OPD at a similar level. The following spreadsheet (Table 2) shows all mentioned parameters per design in comparison.

Part number	S4LFT0080/126 standard lens	S4LFT7010/450 color corrected
lens material	glass mix	glass mix
design wavelength	1064 nm	1,000 nm – 1,100 nm
field size per design	39 mm x 39 mm	35 mm x 35 mm
measurement wavelength range	967 nm – 1067 nm	930 nm – 1030 nm
OPLD difference (field center)	150 µm	169 µm
OPLD difference (field corner)	174 µm	171 µm
OPLD difference each wavelength (center - edge)	154 µm	200 µm
lateral color error (field corner)	198 µm	4 µm
chromatic focal shift (center)	751 µm (diff. Limit: 107 µm)	104 µm (diff. limit: 390 µm)

Table 2: Comparison between standard lens and color corrected lens per design

Mechanical Design

Figure 4 shows a section through a customary F-Theta objective. The lenses are mounted inside a tube in a stack assembly. Each two lenses are kept in a certain distance to each other, with the help of a spacer ring in between. Every lens element is optically centered and is fitted in the housing. Some of the lenses had to be produced with extremely tight tolerances according to their individual sensitivities given by the optical design.

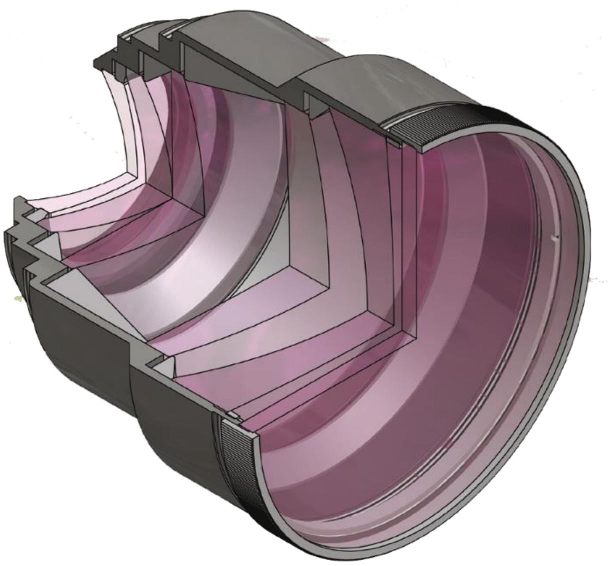

Figure 4: Section through a standard F-Theta lens

For easy mounting, the aluminum housing (Figure 5) is designed with an M85x1 thread, which is a common standard for laser scan heads. The aperture stop distance and mirror spacing was adapted to usual scan heads, that are recommended for the use with a 10 mm laser beam. The objective is equipped with an exchangeable protective window (knurled part).

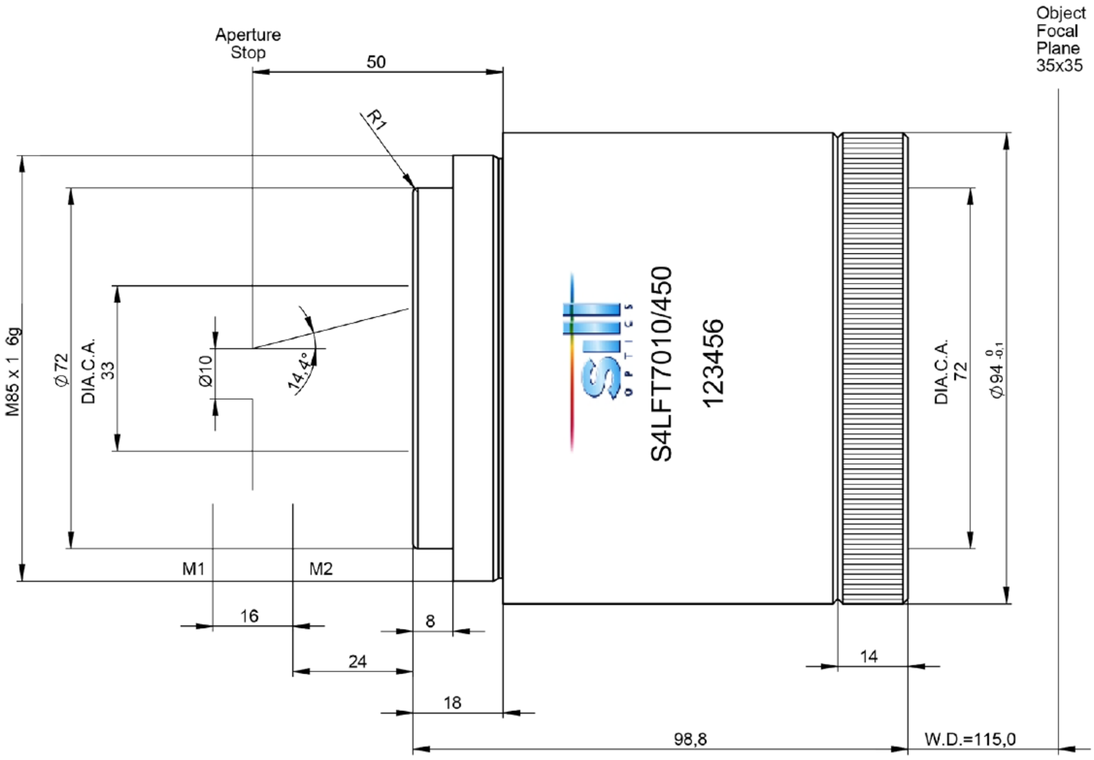

Figure 5: Outline of the new scanning objective

Production and Coating

The production of each lens element starts with cutted discs from the raw glass material. Every lens was grinded, polished, centered and coated before assembly. In order to design a color corrected objective, a certain mix of glass types is necessary. This mix has to be a special combination of low and high refractive glasses. A coating that is designed for low refractive glasses has to be modified for higher refractive glasses. The new scanning objective consists of six optical elements. The different refraction indices made it necessary to perform eight coating runs (four groups of lenses, double sided coated). Figure 6 shows a measured coating curve on BK7 for the used Sill-coating /450.

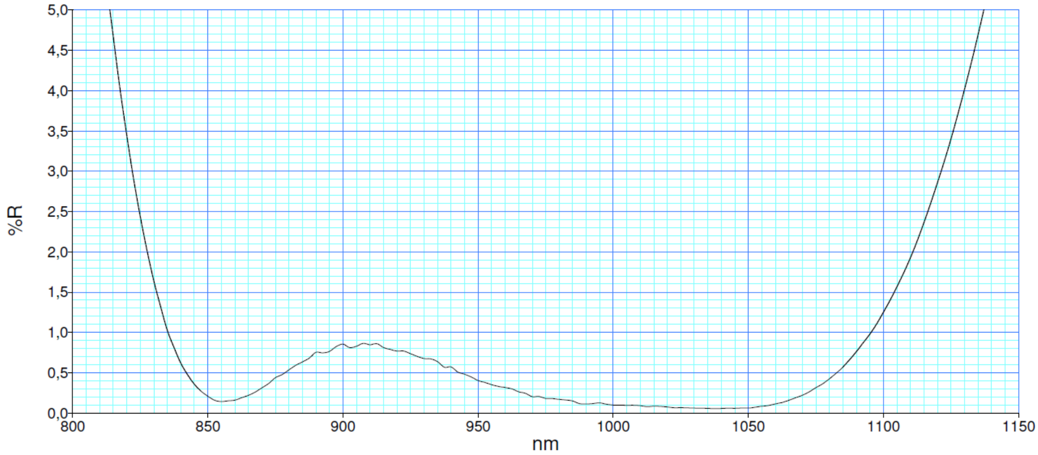

Figure 6: Measured reflectivity per surface in percent

Assembly and quality inspection

The quality test is implemented as a two- or more step process. At first the single lens elements are measured on all geometric properties and wavefront. This happens during and after the production process, to keep all elements in the required field of tolerances. During the coating process the allocation of the optical elements is getting lost. Because of that all lens parameters are recorded after the coating of the lenses. After a final check of cleanliness the lenses are ready for assembly.
With help of the gathered lens information it is possible to go back to the Zemax design and optimize the design for a maximum of performance. **Figure 7** shows the spot performance and lateral spot deviation from the real lens after assembly in comparison to the perfect design lens. In both cases the airy disc (black circle) has a diameter of 12.7 µm. This means that the performance of the real lens is still diffraction limited and the real lateral color error is smaller than 10 µm.

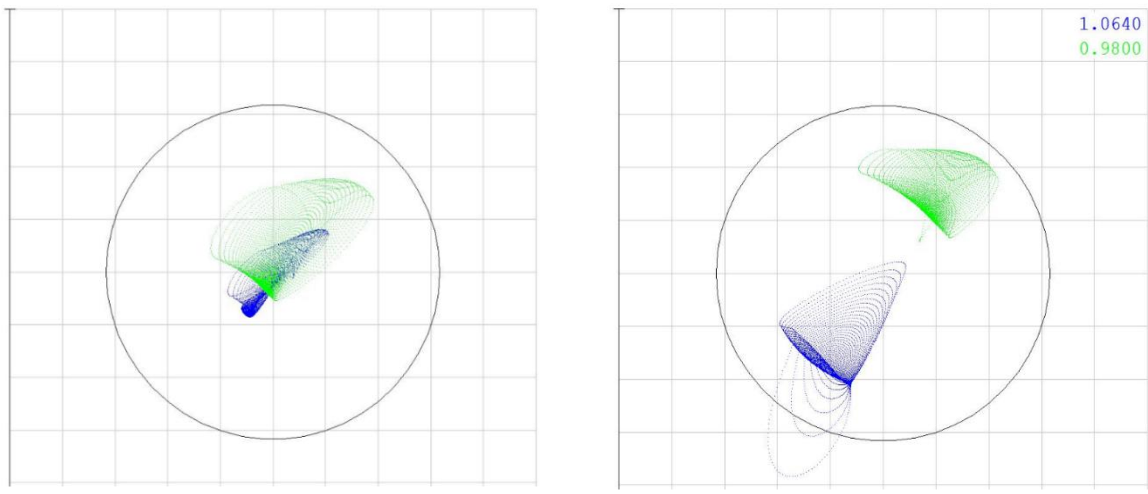

Figure 7: Spot diagrams for f-Theta lens per design (left) and real (right) in the corner of the scan field

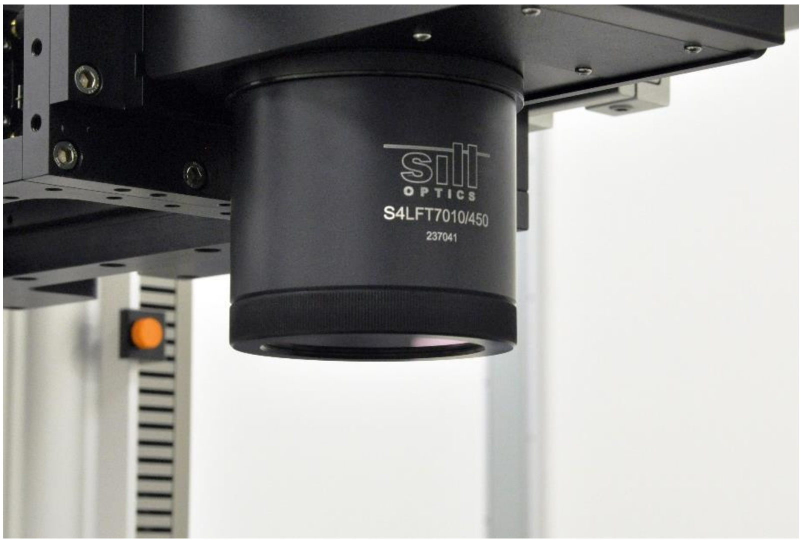

Figure 8: Image of assembled scan lens attached to scan head

Conclusion

The color corrected scan lens is performing very good in the field trials at Lightmotif. It is meeting the requirements for the laser path as well as for the measurement path. It is planned to improve the measurement accuracy and the spot performance further. Thus, a second generation lens will be developed for a green laser.