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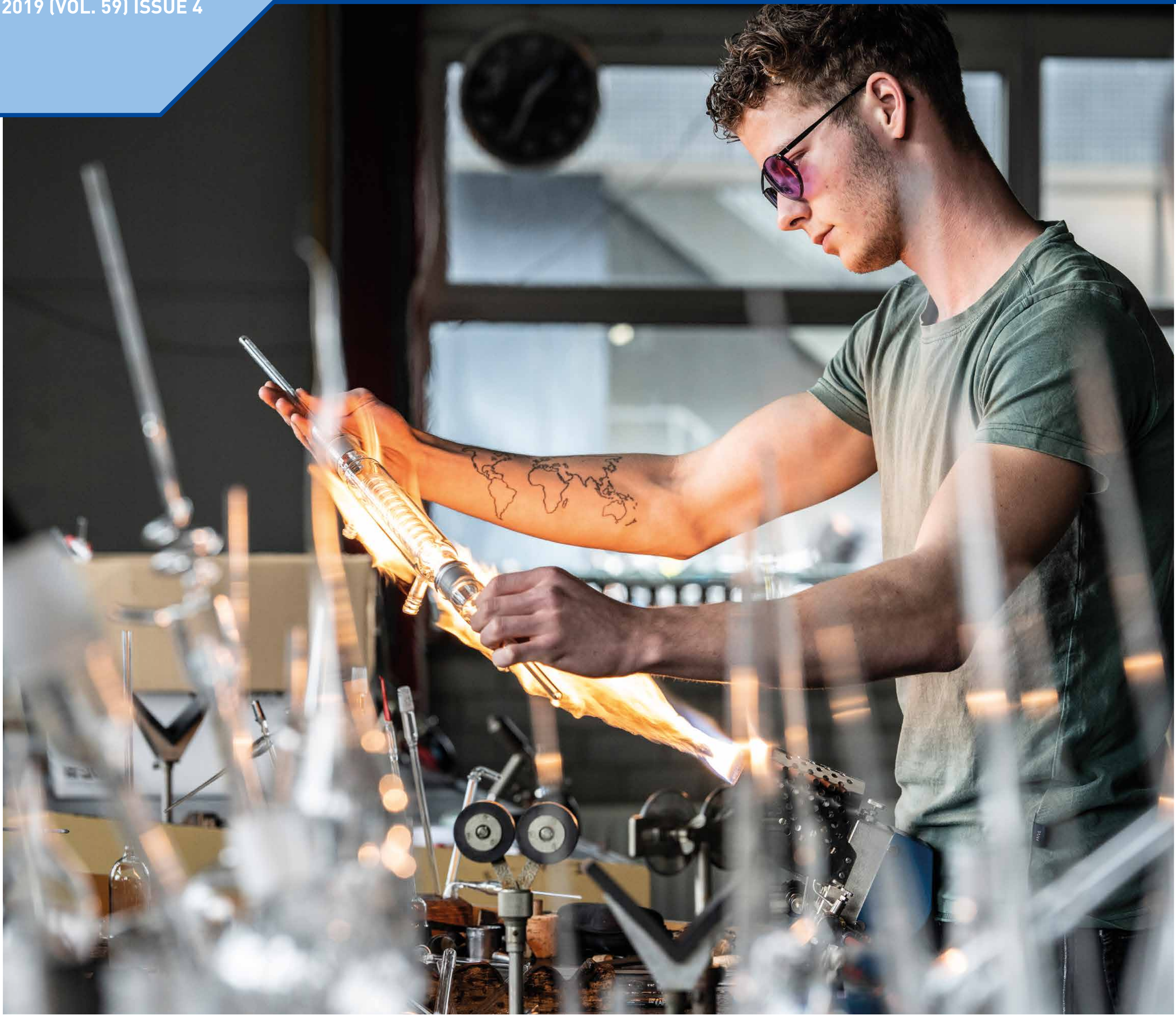

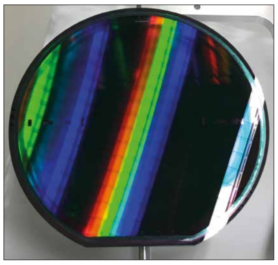

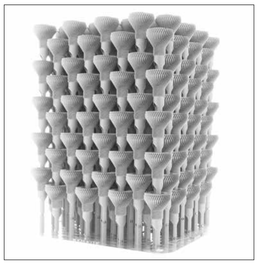

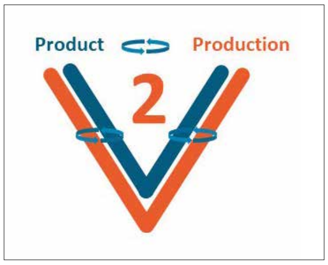

- THEME: MANUFACTURABILITY
- LIS: MAINTAINING HIGH STANDARDS, TAKING NEW DIRECTIONS
- VALUE ENGINEERING IN HIGH-TECH
- EUSPEN CONFERENCE REPORT

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Publisher
DSPE
Annemarie Schrauwen
High Tech Campus 1, 5656 AE Eindhoven
PO Box 80036, 5600 JW Eindhoven
info@dspe.nl, www.dspe.nl

Editor
Hans van Eerden, hans.vaneerden@dspe.nl

Advertising canvasser
Gerrit Kulsdom, Sales & Services
+31 (0)229 – 211 211, gerrit@salesandservices.nl

Design and realisation
Drukkerij Snep, Eindhoven
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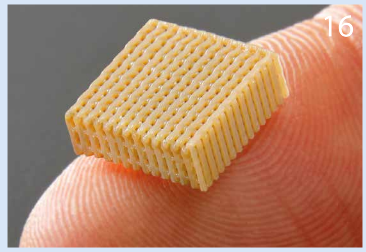
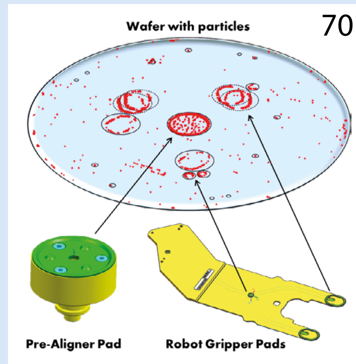
THEME: MANUFACTURABILITY





FEATURES

SMART PARTS, SMART MANUFACTURE...

The sophisticated machines and equipment of the Dutch high-tech industry contain many complex parts. As early as during the development phase there is close contact with suppliers in order to safeguard the manufacturability of these parts with respect to cost price, delivery time and quality. Integration of design, manufacturability and production process is crucial, and software is the connecting factor.

"First time right" is key, so no mistakes. This is only possible if the entire production process is controlled and there are design guidelines available that make this possible. A trend in this respect is 'digital twins'; precise software simulations during all stages of the design and production process ensure that the final physical product fully meets the functionality requirements that the designer had in mind.
Production processes must be capable of processing digital product information and delivering predictable quality. The most important processes are CNC machining (subtractive) and 3D printing (additive manufacturing). The combination of these two main categories (hybrid production technology) is fully in the spotlight. Machining operations are carried out on 3D-printed parts, for example for the application of precisely defined interface surfaces or for achieving the desired surface roughness.

Some of the unique selling points of 3D printing are:
- the rapid manufacture of prototypes and mock-ups (rapid prototyping);
- the great design freedom (both external and internal complex shapes), enabling the manufacture of complex, unique products (e.g. medical implants);
- the optimisation of parts for the desired mechanical properties (strength, rigidity, mass, natural frequency, thermal and fluid properties);
- the integration of components in a monolithic structure (less assembly, more compact construction, elimination of play);
- the combination of various materials in the same part (multi-material printing).

These USPs of 3D printing enable the Dutch high-tech industry to strengthen its competitive position. Examples of existing applications in the Netherlands are microreactors (Shell STCA), miniature heat exchangers for temperature control in precision devices (ASML), integration of cooling channels in moulds for operational efficiency improvement (RiZZ Plastics, VMT Products), topology-optimised components for the high-tech industry (ASML) and the aerospace industry (Airbus Space), lightweight complex components for aerospace applications (Airbus Space), monolithic adjustment mechanisms for optical instruments (NTS Optel, VDL ETG), and implants for medical applications, such as dental implants (Oceanz), vertebra (BAAT medical, FMI Instrumed), skull implants (Xilloc), and prostheses and ortheses for orthopaedic applications (Buchrnhornen).

A special application of 3D printing is the reverse engineering of machine parts whose product documentation has been lost, such as spare parts for older trains and defence equipment. A CAD model of the desired part is first made using a 3D scan of an existing part, which can be modified if desired. 3D printing is then used to create a lost-wax casting mould based on this model, which is then used to rebuild the 'old' part using casting technology and post-machining (Castlab).
Developments in the field of high-grade production technology, in particular additive manufacturing, are taking place at breakneck speed. Unfortunately, the Dutch high-tech industry is still insufficiently aware of the possibilities of this. The design must take into account the possibilities, features and limitations of the production technology. In collaboration with High Tech Institute, Fontys Centre of Expertise HTSM has developed the "Design for additive manufacturing" course for this purpose.

Sjef van Gastel
Director of Innovative Production Technology, Fontys University of Applied Sciences, Eindhoven (NL)
s.vangastel@fontys.nl
www.fontys.nl/Innovatie-en-onderzoek/High-Tech-Systems-and-Materials.htm
www.hightechinstitute.nl/additive

DIRECT CONTACT BONDING

SRON has produced a set of immersed gratings for ESA's Sentinel-5 mission. Manufacturing them involved the direct bonding of a silicon prism to a thin silicon wafer with etched grating lines. For space mission hardware like this, product assurance and quality assurance requirements are especially stringent. After manufacturing the immersed gratings and integrating them into a support structure, a comprehensive campaign to test the performance of the immersed gratings and their resilience to launch conditions and space environments was organised to qualify the product.

RENÉ WANDERS, PHILLIP LAUBERT AND RALF KOHLHAAS

Direct contact bonding is a remarkable process in which two surfaces are pressed against each other and – under the conditions of perfect parallelism and low roughness of the two surfaces – become a single component by intermolecular forces. For the Sentinel-5 mission, a flagship satellite mission for the measurement of greenhouse gases from the European Space Agency (ESA), special optical components called immersed gratings were needed (Figure 1). Their integration should considerably reduce the instrument size and therefore the cost of the mission.

SRON took the challenge to produce and qualify such immersed gratings for this mission, involving the crucial step of direct bonding of a bulk silicon prism to a thin silicon grating for the first time [3]. This article describes the difficulties encountered, with special emphasis on the space mission aspects.

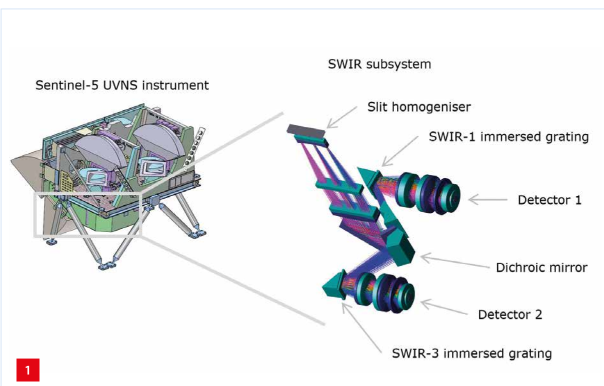
For the detection of greenhouse gases from space, sunlight reflected from earth is detected with a spectrometer which splits incident light in different wavelengths. From the absorbed light at different wavelengths the abundance of different gases in the atmosphere can be inferred.

The heart of a spectrometer is the grating. A silicon immersed grating, shown in Figure 2, consists of a silicon prism (supplied by Thales SESO) with a grating surface on one side containing a series of equally spaced grooves. In the wavelength range of interest (1.6-2.4 μm), silicon is transparent. Light can enter the prism from an entrance surface and hit the grating surface, which subsequently splits the light in different wavelengths. Upon leaving the prism again through the entrance surface, the ability of the grating to resolve different wavelengths is increased by the refractive index of silicon (n = 3.4), which acts as the immersive medium. Due to the increase in resolving power the size of the spectrometer can be reduced.
In order to meet the stringent requirements on the prism (such as an angular accuracy of 90 arcsec between surfaces and a surface flatness of 10 nm rms) and the grating (such as a line periodicity of 2,070 ± 5 nm) a bonding approach was chosen. This allowed to separately produce the prism and the grating pattern on a 150-mm-diameter wafer, unlike the monolithic immersed grating for the Tropomi instrument [4, 5]. For the grating, standard lithography equipment could be used and the best gratings were chosen after production.

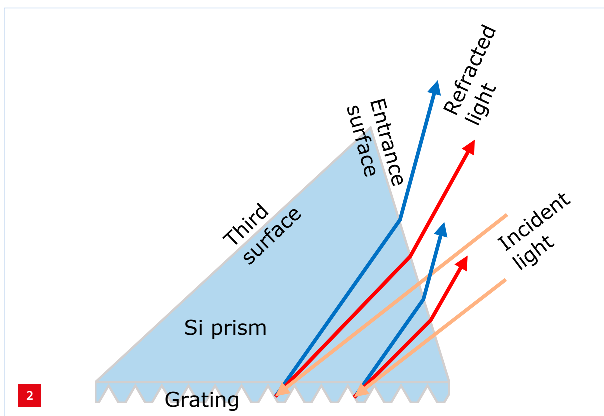
AUTHORS' NOTE

All authors work for SRON Netherlands Institute for Space Research; René Wanders as a mechanical design engineer, Phillip Laubert as a product assurance manager and Ralf Kohlhaas as an instrument scientist and MAIT (manufacturing, assembly, integration and testing) manager for immersed gratings.

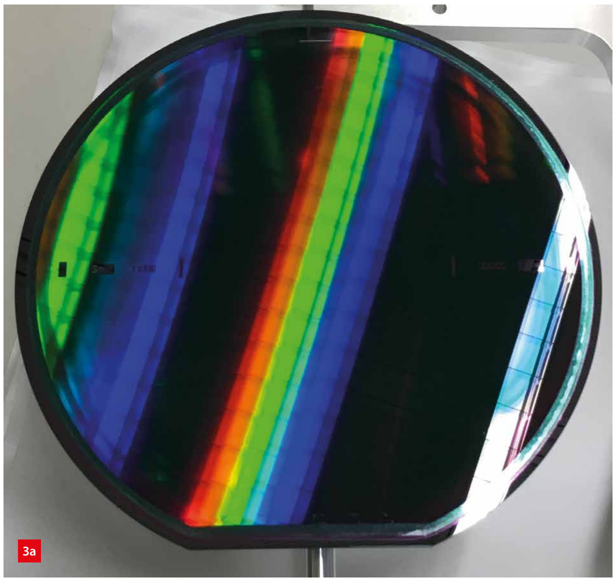
r.m.wanders@sron.nl
www.sron.nl

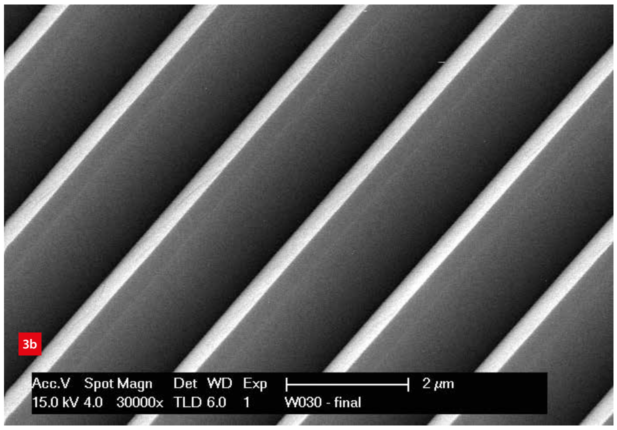


1 *Sentinel-5 UVNS (Ultraviolet Visible Near-Infrared Shortwave) instrument [1] and optical design by Leonardo [2], including the SWIR-1 grating and the SWIR-3 grating (SWIR stands for short-wave infrared).*



2 *Working principle of an immersed grating. The incident beam is wavelength-dispersed by the grating and the prism.*





Example of a grating.
(a) Photograph.
(b) SEM image of grating lines.

Figure 3 shows an example of a grating. The groove pattern was produced at Philips Innovation Services by KOH etching, which yields a very low roughness of the surface along the atomic crystal planes of silicon. Direct bonding of silicon wafers is a standard process in the semiconductor industry.

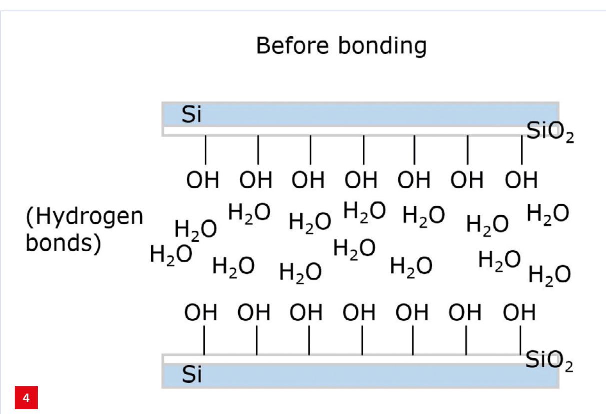
A simplified description of the chemical process taking place in the direct hydrophilic bonding of silicon is shown in Figure 4. After cleaning and plasma activation, silicon reacts with water in ambient air to form Si-OH groups. When two such surfaces are pressed against each other and annealed at high temperature, Si-O-Si bonds are formed. The high chemical bonding strength makes the two components inseparable.

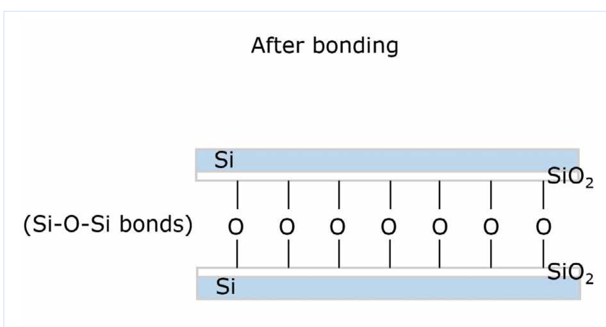
The void-free bonding of a grating with a bulk silicon prism is more challenging than the bonding of two wafers. Only the grating is flexible in this case, which can lead to gaps between the grating and the prism in the bonding process (voids). Furthermore, standard wafer bonders are not equipped to accommodate a bulk prism and are too unstable to fulfil the ±6 arcmin requirement on the orientation of the grating with respect to the prism. For this reason, a standard wafer bonder from AML was modified by SRON (Figure 5).

The bonding procedure

Firstly, the prism was placed in a prism holder structure. The orientation of the prism with respect to the holder was measured in a coordinate measuring machine. Then the prism holder was placed in the bonder and actuators were used to compensate for the measured differences. The grating was clamped to the inside of the lid of the bonder. The prism holder and the grating contain alignment marks and their respective orientations were measured under vacuum through a camera system in the lid of the bonder. Adjusters on the lower stage of the bonder were used to make sure the prism and grating were aligned properly after evacuation of the bonder. An added rotation stabilisation system in the bonder minimised rotational errors during bonding.

The prism and grating were removed to allow cleaning and surface activation, which had to be done within 10 minutes before the actual bonding for a successful outcome. Both were placed back in the bonder and the surface was inspected one last time for cleanliness.





Hydrophilic bonding of silicon.

SENSOR-BASED ADAPTIVE LASER MICROMACHINING

Within the Horizon 2020 project Adalam, a novel depth sensor has been successfully integrated into a laser micromachining system. This new sensor allows the machine to get feedback on the real machined depth, which is used to automatically adapt the micromachining process. The process results in an increased depth accuracy of the machined structures. This article describes briefly the novel depth sensor, its integration into an existing laser machine, and the results obtained when using this adaptive laser micromachining system.

ALBERT BORREMAN, LÉON WOLDERING, ERIK-JAN DE HOON, MAX GROENENDIJK, MANUEL ZENZ, ROUWEN KUNZE AND ROBERT SCHMITT

AUTHORS' NOTE

Albert Borreman (business unit manager Focal opto-mechatronic systems), Léon Woldering (group leader optical and vision engineering) and Erik-Jan de Hoon (senior project manager Hightech systems) all work with Demcon in Enschede (NL).
Max Groenendijk is the CEO of Lightmotif in Enschede.
Manuel Zenz is a project manager at Sill Optics in Wendelstein, Germany.
Rouwen Kunze is group manager Optical Metrology and Imaging Methods at the Fraunhofer Institute for Production Technology (IPT) in Aachen, Germany.
Robert Schmitt is division director Production Quality and Measurement at Fraunhofer IPT, and profesor of Metrology and Quality Management in the Laboratory for Machine Tools and Production Engineering (WZL) at RWTH Aachen University.

albert.borreman@demcon.nl
www.demcon.nl
www.lightmotif.nl
www.silloptics.de
www.ipt.fraunhofer.de
www.wzl.rwth-aachen.de

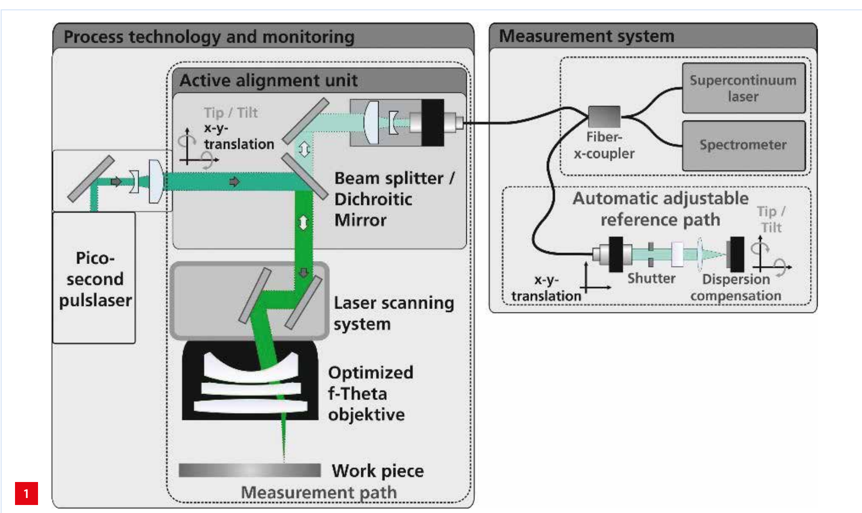
Introduction

The inline topography measurement concept (Figure 1) [1] integrates a depth sensor based on a frequency-domain low-coherence interferometer (FD-LCI) [2] into the beam path of a laser micromachining system [3]. The integrated depth sensor can be used to:

- measure the surface topography before machining, to scan for existing surface deviations that can be removed in an automatically generated machining process;
- measure complexly shaped objects prior to machining, to precisely align the machining pattern to the workpiece;
- measure the surface topography while machining a part, in order to adapt the micromachining process, leading to highly increased machining accuracies and no defects;
- quickly validate results after machining.

Sensor concept

The sensor uses the optical interference effect between a reference path and signal path to derive the optical path length difference between these two branches, see Figure 2. The longer the optical path length difference between reference and measuring branch is, the higher the resulting modulation frequency will be. The calculation of the Fourier transformation of the acquired spectrum provides a spectral intensity as a function of the depth. Therefore, for each scanned position, an intensity peak is derived at the distance that represents the depth of the sample [4].



1 *Overall system concept including the laser milling modules (picosecond-pulse laser, 2-mirror galvo-scanner laser-scanning system, F-theta lens) and the depth sensor (measurement system, active alignment unit).*

An advantage of the FD-LCI measurement principle over other optical measurement principles is that it can be developed to work in different wavelength ranges. This enables the adaptability to different application requirements.

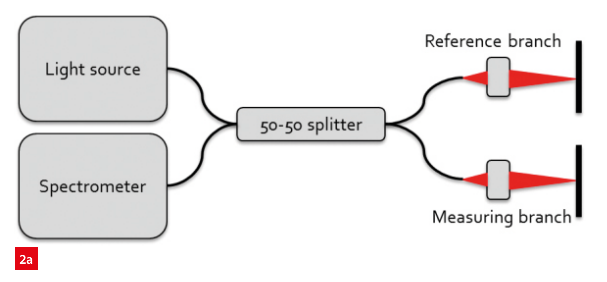
The axial resolution for topographic measurements and the measurement range of an FD-LCI system using a Gaussian-shaped light spectrum are given by Tomlins et al. [5]:

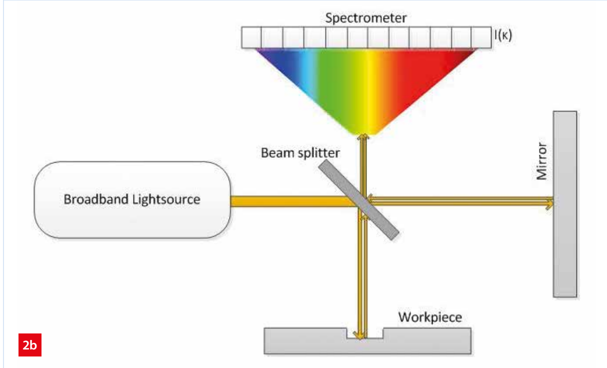
$$Depth_{resolution} \approx 0.44 \frac{\lambda_0^2}{\Delta\lambda}$$

$$Depth_{range} = \frac{N}{4n} \frac{\lambda_0^2}{\Delta\lambda}$$

Here, λ_0 is the centre wavelength, and $\Delta\lambda$ the FWHM (full width at half maximum) of the light source. N is the number of pixels of the detector, and n is the assumed average sample refractive index.

To maintain an optimal interference signal while scanning a sample with varying reflectance, the reference path has to be adjusted such that it matches the varying reflected light from the surface. Within the Adalam project [1, 2] an automatically adapting reference path module with a bandwidth of 400 Hz has been successfully developed [6]. Furthermore, the sensor was designed such that it operates at wavelengths near the laser milling wavelength of 532 nm. To be precise, the wavelength range of the sensor beam was





Spectral-domain low-coherence interferometer.
(a) Schematic set-up.
(b) Schematic of the light paths.

selected to be 540-595 nm. By doing so the optical path of the sensor and of the laser milling system can be combined in the final part of the optical axis of the machine [6].

The sensor has been successfully developed and tested by Fraunhofer IPT and Demcon. The measurement reproducibility was found to be ±1.5 μm, the measurement range is 900 μm. The initial measurements showed that at the darkest pockets the exposure time is near 1 ms, while at shiny pockets the exposure time is about 0.4 ms [7]. The laser milling beam and the sensor beam have a common path through the F-theta lens.

To avoid aberration of the measurement spot, the F-theta lens had to be optimised for a minimum lateral colour error as well as a minimum chromatic focal shift for the whole wavelength range. Within the Adalam project, Sill Optics successfully developed a colour-corrected F-theta lens that covers 515 nm up to 595 nm with a lateral colour error of less than 5 μm and a chromatic focal shift of less than 30 μm [8].

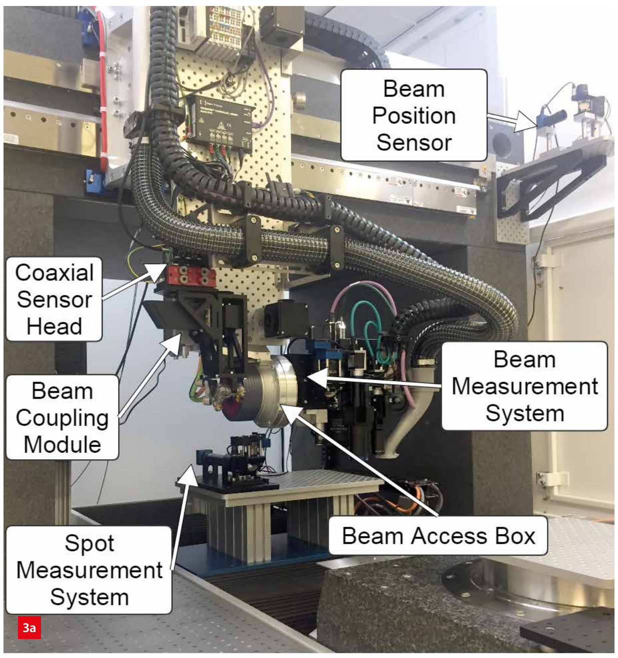
Integration

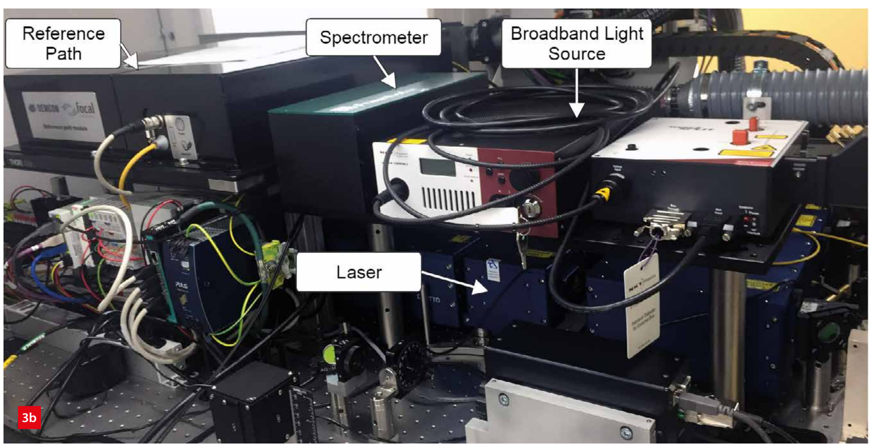
In order to be able to integrate the sensor into the milling machine, three additional measurement tools have been developed:

1. A coaxial sensor head for the alignment of the sensor beam, which is also called the active alignment unit.
2. A beam measurement system that can measure both the laser milling beam and the sensor beam to allow proper alignment and overlap of these two beams.
3. A spot measurement system to measure and compensate for changes over the entire scan field. This system is also used to determine the location of the scan field relative to the machine.

The different components of the measurement system have been successfully integrated into the 5-axis laser micromachining system of Lightmotif; see Figure 3.

To be able to perform depth measurements in machine coordinates, the depth measurement system needs to be calibrated. In particular, the depth and the depth offset have to be calibrated, as well as the centre position and the lateral dimensions.





Overview of the measurement system.
(a) The integrated modules in the 5-axis laser micromachining system.
(b) The relevant components for the depth measurements.