# Ultra-precise machines for hybrid optical elements

Replicated curved **DIFFRACTIVE** optical elements are used, e.g. to miniaturise spectroscopic systems, although manufacturing the masters is time consuming and cost intensive. Flexible ultra-precision machining provides greater freedom in optical design but requires precise control of machine tool and process.

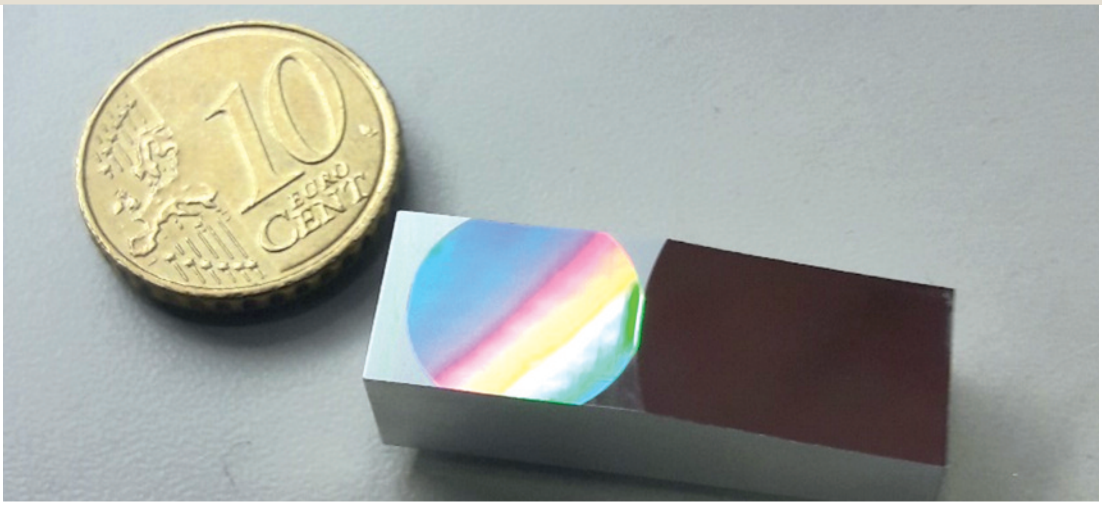


**Figure 1. Monolithic integrated optics in aluminium RSA: concave curved diffraction grating and toroid mirror**

**KURT HASKIC AND DIRK OBERSCHMIDT**

As a part of optical analytics, optical spectroscopy is an interdisciplinary technology in various growth markets, including industrial sectors like medical technology, energy, and aerospace. The current trend towards miniaturisation while simultaneously increasing the functional integration level, combined with increasing customisation and growing cost pressure, calls for flexible production methods that are capable of meeting the stringent quality standards for optical analytics.

## Increasing requirements for miniaturised hybrid optics

The increasing customisation and decentralisation of spectroscopic instruments means that the market is facing a transformation that is yielding increasing demand for compact spectrometer subsystems and components. Along with volume reduction, customers require simultaneous reduction in costs, but constant measurement capabilities.

Spectrometers are made up of at least one optical grating and imaging elements for beam shaping. Blazed gratings with triangular microstructure geometry are often used to improve efficiency. More compact optical designs with a reduced number of boundary surfaces can be created using curved diffractive optical elements, which combine imaging and dispersive properties. This allows miniaturisation without compromising the efficiency. Such optical elements normally involve complex one-off production. They can be used directly as high-end product or be supplied to mass markets by replication of master

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Figures: LT Ultra (1), TU Berlin (2)

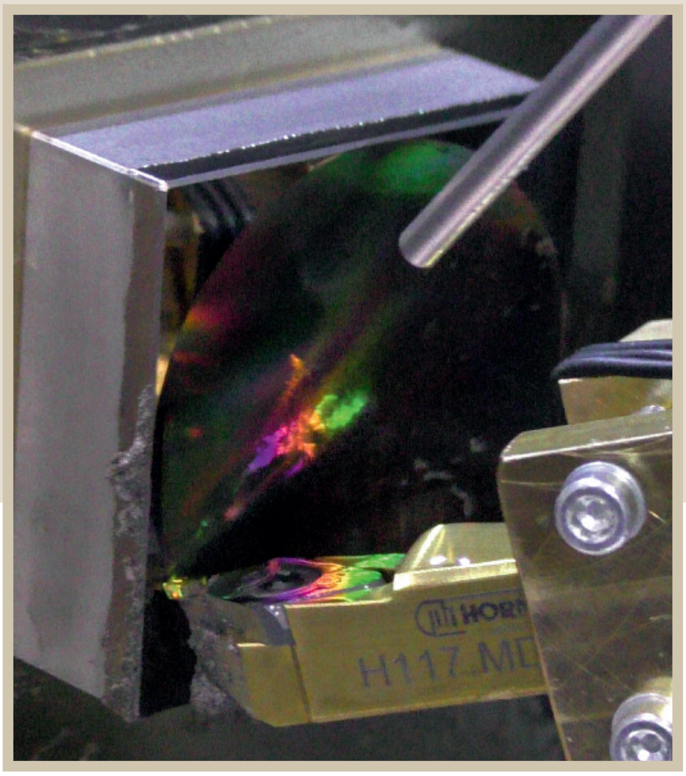


**Figure 2. Ruling nickel phosphorous (NiP) hybrid optics**

structures. Individual optical elements as well as master structures can be manufactured by means of ultra-precision (UP) machining or lithographic methods.

The manufacture of blazed gratings using ultra-precision (UP) technologies offers significant advantages regarding the design of hybrid optical elements, i.e. individual components with an increased design freedom, as well as directly manufacturing of moulds and dies for replication. This not only means an advancement in customer applications but also paves the way from complex manufacturing of these optical elements onto their reliable replication process for e.g. high-resolution spectrometers **(Figure 1)**. The necessary enhancements and adaptations of machinery and process technology to handle the specific requirements of optical gratings have been developed through close cooperation between the companies LT Ultra-Precision Technology and Carl Zeiss Jena, along with the Technische Universität Berlin, as part of a research project supported by the German Federal Ministry of Education and Research (BMBF).

## Mechanical micro and nano machining

Depending on the spectral range of the optical components, forming or cutting production methods are used. The grooves are individually cut or formed into the substrate by means of relative motion between tool and workpiece on straight or curved paths. The diffractive surface of the grating is created by incremental displacement of the tool. Tools are mono-crystalline diamonds and must fulfil strictest requirements regarding shape and tolerances.

While groove machining using forming, the mono-crystalline diamond tool is pressed onto the surface of the grating blank with a defined force. This results

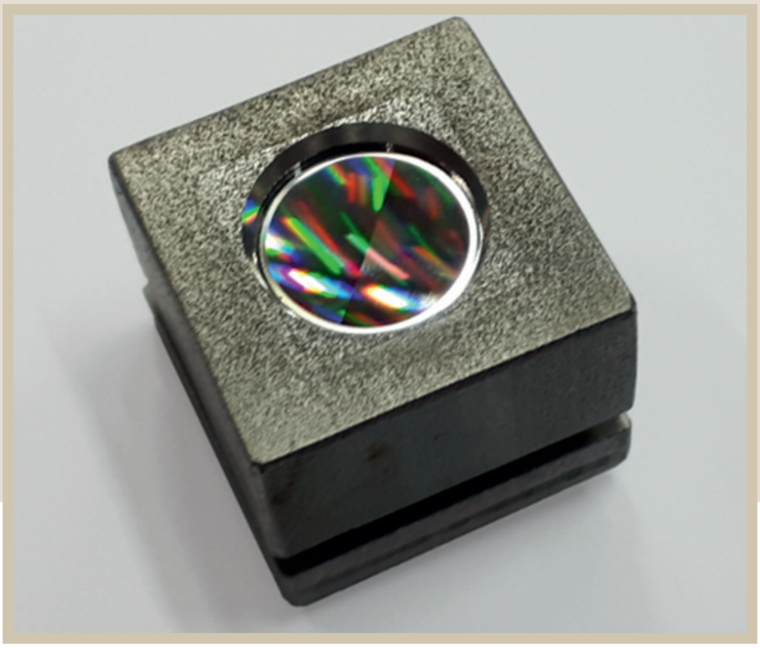

**Figure 3. A curved, diametrically-ruled grating covering two spectral regions, made in NiP as that can be used as a master for replication tasks**

in plastic deformation, so that the projected tool geometry creates the shape of the grating grooves. The alignment of the tool and the set force are subject to narrow tolerances. To achieve this, the TU Berlin created the required parameter models and developed a special module for adjusting the grooving tool. This was done based on flexure hinges. Constant force is provided by precision weights or voice coil actuators. A specially developed laser triangulation module is used to adjust the angle of the tool relative to the workpiece's surface.

An alternative to forming is planning (cutting) of the grating grooves **(Figure 2)**. Tools used for this process are diamonds with precisely manufactured profile edge. The path-controlled manufacturing method is notable for its comparatively wide process window and associated high level of design freedom, but involves extremely stringent requirements in terms of vibration damping, temperature stability and process control. Measures for the fulfilment of these requirements help to avoid damages, e.g. due to chip flow or built-up edges.

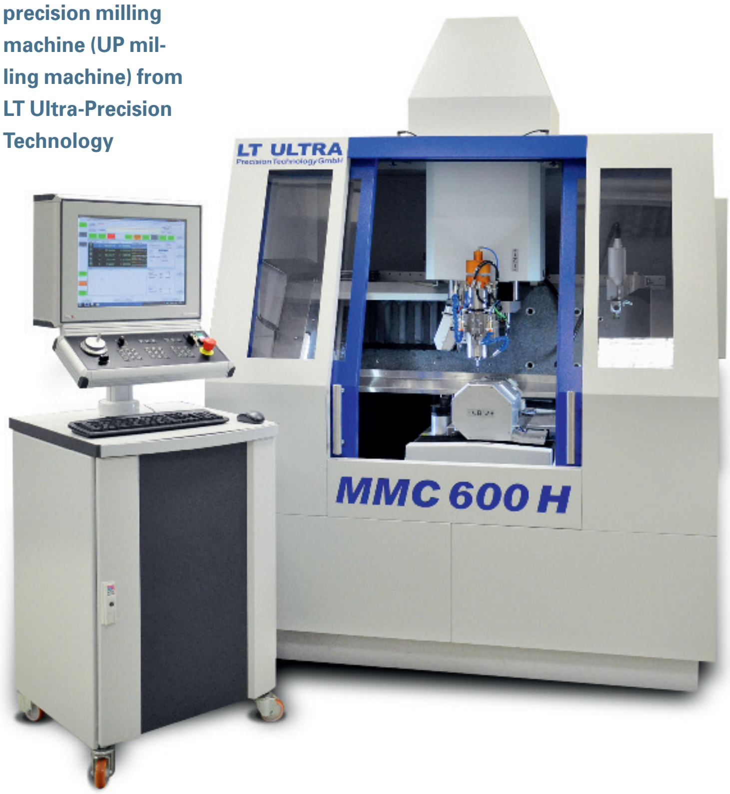


**Figure 4. Type ›MMC 900H‹ ultra-precision milling machine (UP milling machine) from LT Ultra-Precision Technology**

## UP machining with a wide variety of materials

A further key advantage of UP cutting and forming technologies is the wide variety of machinable materials. For example, electroless deposited nickel-phosphorous is X-ray amorphous and suitable for mould construction **(Figure 3)**. One-off products for the aerospace technology sector can be manufactured using gold or aluminium layers depending on the spectral range. Material-specific process parameters for grating production were investigated by TU Berlin carrying out machining tests and accompanying simulations. To set up the simulation environment based on a Johnson-Cooke model, the material parameters were adapted by use of experimental data and validated by means of force measurements resulting from actual experiments.

Coated optical elements tend towards delamination of the optical functional layer under (alternating) thermal or mechanical loads. Therefore, in these conditions monolithic, homogeneous elements are preferred. In the visible spectral range, aluminium alloys are widely used due to their high reflection coefficient. At TU Berlin, gratings manufactured from various ultra-fine grain RSA aluminium alloys were investigated. As a result, optimised processing parameters are now available for the machining of especially RSA 501. Thus, the coating of optical elements is often not necessary. Furthermore, other optically effective surfaces, for example mirrors, can be combined with the grating. These hybrid optical elements can be produced without reclamping processes. No adjustment operations are necessary and positioning accuracies of better than 1 µm can be

Figures: LT Ultra (4,5), TU Berlin (3)

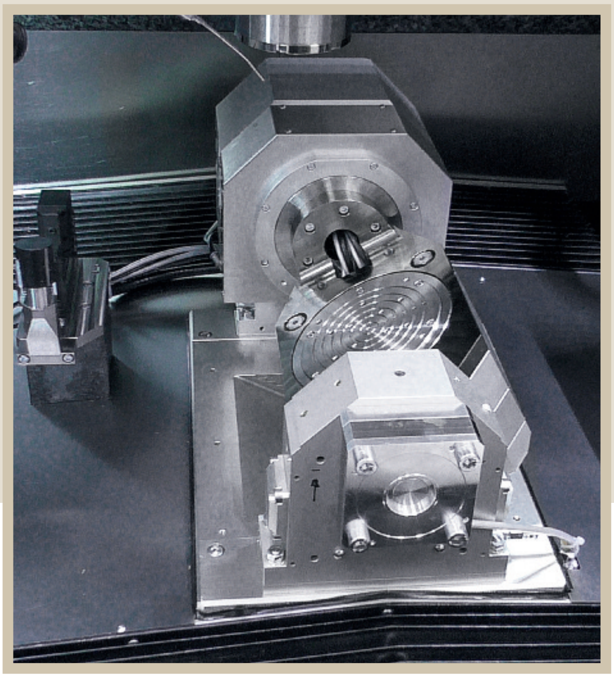

Figure 5. UP tilt/swivel unit for 5-axis simultaneous machining from LT Ultra-Precision Technology

achieved. To create a suitable platform for production of hybrid optics, a ›MMC 900H‹ machining center from LT Ultra was modified. Various functions were added and existing systems were optimised for the specific application **(Figure 4)**.

## Air tempering of UP machines

Depending on the production method, workpiece size and structural dimensions, production of hybrid optics can take anywhere between an hour and a week. Constant ambient conditions are crucial to exclude any unwanted deformation of the workpiece, which would otherwise distort the wavefront, for example. To achieve this, the machine concept was enhanced with additional air tempering. This involves an add-on unit that has since been integrated into other LT Ultra systems. The air in the process area is circulated with the addition of a small quantity of fresh air supply and is tempered by precision coolers. This method is considerably easier than high-precision climate control of the entire machine installation space, for example.

The air circulation allows efficient regulation of the temperature as only the heat output from the process and the machine enclosure (ambient temperature) has to be compensated. Tests on UP milling machines reveal potential energy savings of at least 25 percent.

The add-on unit also complies with the Atex directive, allowing safe working with any flammable or explosive cooling lubricants. Different air filter levels can be used for operation in a cleanroom or grey room environment. This system enabled a temperature constancy of ±20 mK to be achieved over a period of one week. As a result, it represents a suitable cooling solution for even the most demanding processes.

## UP tilt/swivel unit

To achieve the high production accuracy required, a new UP tilt/swivel unit was developed and implemented **(Figure 5)**. The tilt/swivel unit is equipped with direct drive torque motors with no additional gearing. Combined with the hydrostatic bearing and using glass scales, an unrivalled positioning accuracy can be achieved with backlash-free positioning. The set objectives of the research consortium – stiffness values of more than 100 N/µm and radial and axial runout of better than 50 nm – were exceeded, with ▶

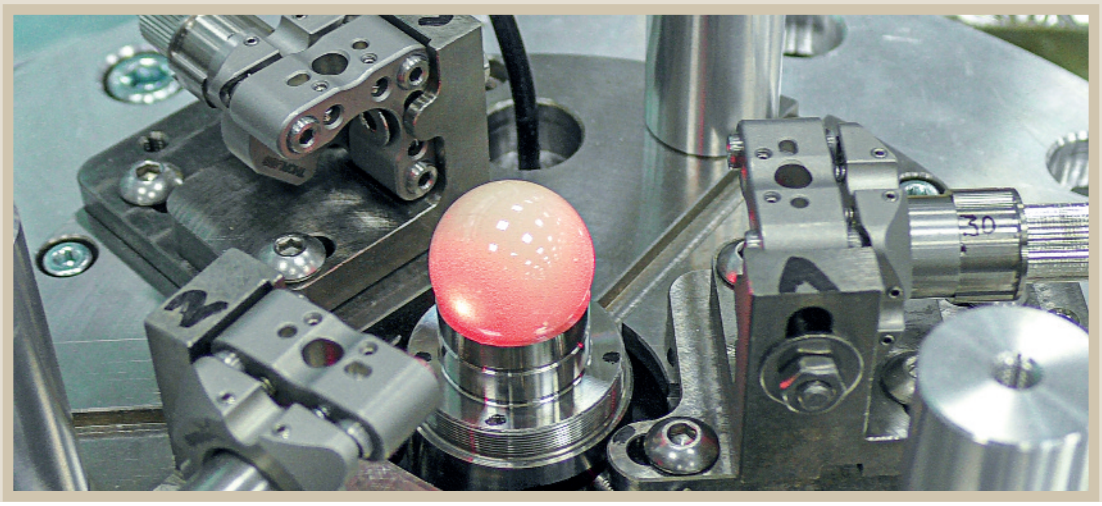


**Figure 6. Interferometric radial and axial runout measurement from LT Ultra-Precision Technology**

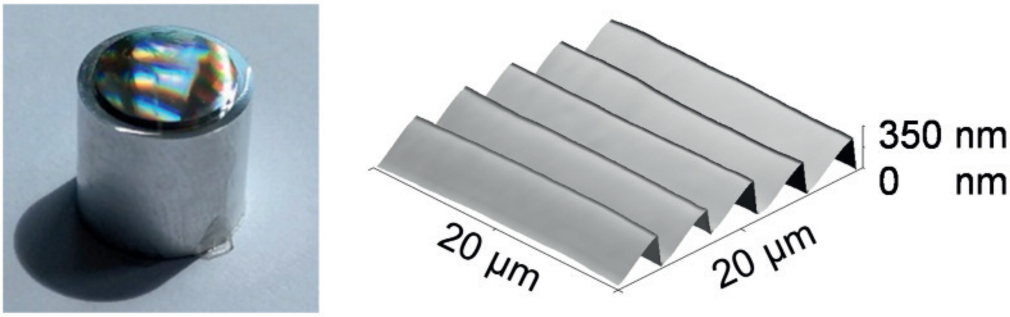


**Figure 7. Convex curved diffraction grating in RSA aluminium with topography of the grating structure**

results of 500 N/µm and 40 nm respectively. The vacuum chuck with 120 mm clamping diameter and swivel range of ±95° guarantee total flexibility.

## High-precision radial and axial runout measurement

To enable the quality to be verified, a test rig was developed to determine the radial and axial runout of the rotational axes **(Figure 6)**. It uses an interferometric measurement technique and an evaluation algorithm developed by LT Ultra and the TU Berlin to record, process and visualise the axis errors. The four sensors used in one plane thus compensate for alignment error and irregularities of the measuring standard and the algorithm returns ›only‹ the axis error. This is critical, as even the best measurement standards have an irregularity of 20 to 50 nm. At present, development of the system is continuing to allow it to be used in multiple planes and in various product families available from LT Ultra, for example on high-speed spindles.

## Inline measuring technology

To improve quality control and reduce setup times, the system has been equipped with an additional measurement axis. On this axis are an atomic force microscope (AFM), a tactile measurement system and an optional high-resolution microscopic camera. This enables workpieces to be fitted and pre-measured with optimum accuracy.

The AFM enables an initial inline quality estimate after production of just a few structures **(Figure 7)**. There is no need to remove the hybrid optics to measure the structure outside of the machine and then re-install with the required accuracy. As a result, possible errors can be detected very early, which would otherwise only be visible when the time-consuming production was complete.

## The consortium

As part of the ›3D Blaze‹ research project (SME innovation: Photonics, supported by the BMBF), Carl Zeiss Jena, LT Ultra-Precision Technology and Technische Universität Berlin jointly developed a machine and process technology for mechanical production of hybrid optics. The technologies created are not in competition with existing lithographic production technologies but represent a complementary addition to the application-specific manufacturing portfolio in the diffraction grating industry. ■

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Figures: LT Ultra (6), TU Berlin (7)