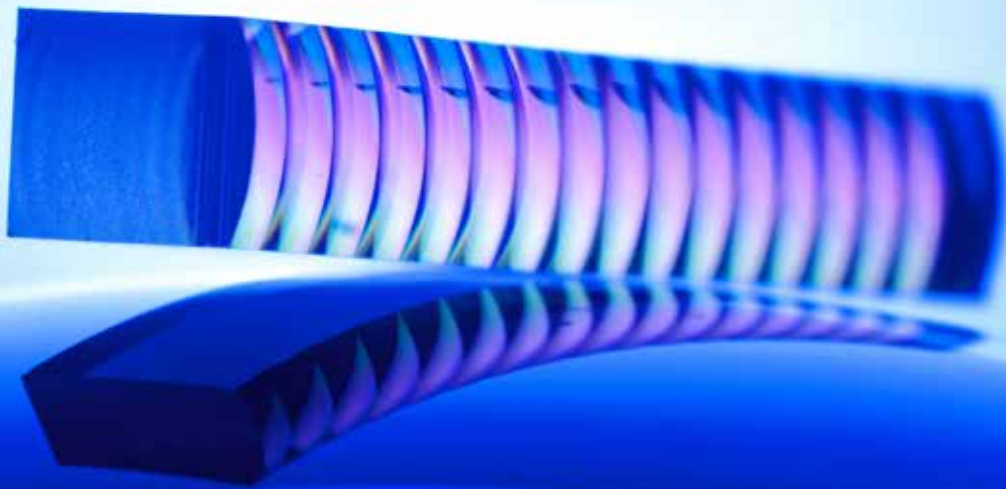


CASE STUDY

How microlens arrays help measure the color of oceans



Authors:

Dr. Stefan Hambücker

Dr. Chhavi Jain

Luis A. Ramos-Izquierdo

Alejandro Perez Rodriguez

(Managing Director), INGENERIC GmbH, Aachen, Germany

(Product Development Engineer), INGENERIC GmbH, Aachen, Germany

(Optical Systems Engineer), NASA Goddard Space Flight Center, Greenbelt, MD, USA,

(Optical Engineer), SGT Inc., Greenbelt, MD, USA

As part of NASA's PACE project, a spectrometer in orbit will measure the „color of the ocean“ – the intensity distribution of light in several closely spaced wavelength ranges with unprecedented spectral resolution. An important component of this is a microlens array from INGENERIC, which couples the received light in the short-wave infrared with high efficiency into a glass fiber bundle.

As part of the PACE (Plankton, Aerosol, Cloud, ocean Ecosystem) mission, NASA is planning to measure the „color of the oceans“ from a satellite scheduled to launch in 2022. The mission will help scientists investigate microscopic ocean organisms that play a significant role in feeding marine life, aerosols, and clouds – and the role all of these play in the Earth system.

OCI – Ocean Color Instrument

The central instrument of the PACE Satellite is a highly advanced optical spectrometer called the Ocean Color Instrument (OCI), that measures properties of light from ocean environments over portions of the electromagnetic spectrum from ultraviolet to short-wavelength Infrared (SWIR). A schematic showing the planned layout and principle of OCI can be seen in Fig. 1(i) and 1(ii) respectively.

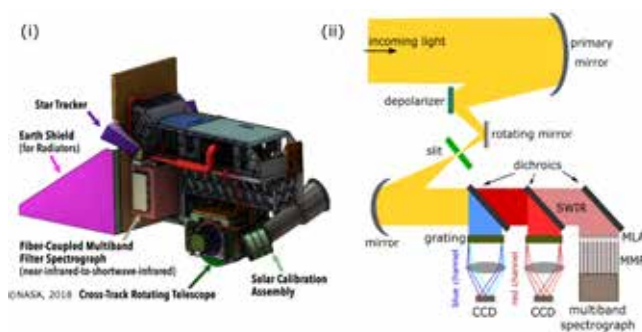


Figure 1:

- (i) Schematic of the planned Ocean Color Instrument (OCI) showing different sub-systems.
- (ii) Schematic of the working principle of the OCI (CCD: CCD sensor; SWIR: short wavelength infrared; MLA: microlens array; MMF: multimode fiber)

Its advantage to previous NASA satellite sensors is its hyperspectral capability, i.e. improved spectral resolution of 5 nm when measuring the spectral range between 350-885 nm and large signal to noise ratios (SNRs). Moreover, to retrieve accurate ocean optical properties, OCI can remove unwanted reflectance contributions from the atmosphere (e.g. aerosol reflectance) and ocean surface. This atmospheric correction especially for near-shore regions or turbid waters is performed in the SWIR range where water absorption

is few orders of magnitude greater than in the near infrared, ensuring nearly zero ocean reflectance.

The PACE Team at the Goddard Space Flight Center is currently developing the system to meet performance standards from scientists studying the atmosphere, ocean and even land surface.

The planned satellite will orbit around earth's northern-southern hemispheres at an altitude of 675 km and consists of a cross-track rotating telescope that makes 360 rotations per minute and has a field of view of $\pm 56.5^\circ$. For every instance in time, the telescope records an array of 1×16 spatial pixels also called "science pixels" by NASA where each pixel amounts to a 1×1 km geographical area measured at Nadir. Furthermore, to ensure high SNRs by building enough signal for integration, the telescope views the same geographical scene on earth for an extended time by imaging every "science pixel" 16 times, as it rotates.

This broadband light signal from oceans (acquired in the form of 16 spatial pixels) is reflected off a primary mirror (an off-axis parabola), depolarized and projected onto a rectangular slit. Thereafter, it is collimated and redirected using dichroic beam splitters to blue and red hyperspectral channels where dispersive gratings separate the individual wavelengths respectively and image them on time delay integration-charged coupled devices (TDI-CCDs). The SWIR bands are analyzed using a remotely located multi-band filter spectrograph that contains a temperature cooled 1×16 detector array. To couple light into the detector array, a 1×16 bundle of 600 μm core sized multi-mode fiber (MMF) with a numerical aperture of 0.22 is used. This is a superior approach than using 16 individual lens systems to couple incoming light from

telescope to the detector array where precise mechanical alignment is cumbersome and prone to errors.

For efficient coupling of collimated light into the MMFs, NASA decided to use aspherical microlens arrays (MLA) with the requirement of low coupling losses. To minimize polarization dependent losses, both the MMFs and the MLAs required broadband anti-reflection coating from 0.9 to 2.3 μm . The goal is to be able to couple light over the entire spectrum with an efficiency of 95 percent.

The selection process

For the initial testing phase, NASA obtained commercially available lithographically produced quartz MLA with a pitch (lens center-to-center distance) of 1.3 mm. To determine the performance of the MLA, the surface profile of individual lenses was measured and compared with the desired lens surface profile where considerable deviations in surface sag profile at the lens edges of the lithographic lens were found (Fig. 2 (i)). During optical simulations with commercial software Zemax, the measured surface sag errors at edges showed an increase in the spherical aberration at the image plane, which has the consequence of decreased coupling efficiency into fibers.

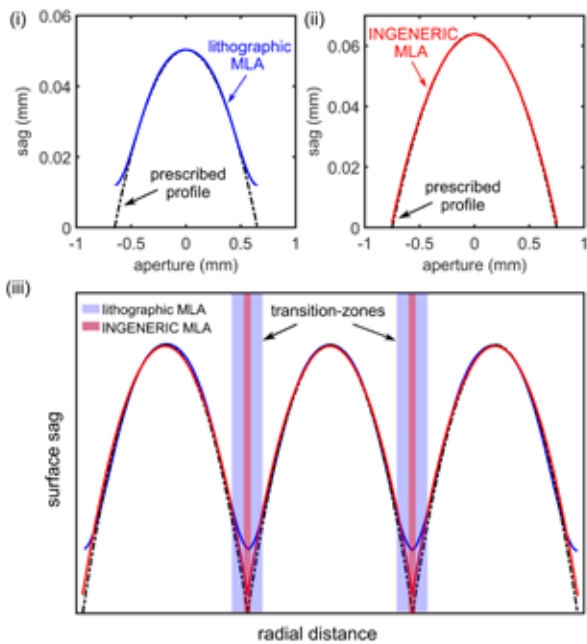


Figure 2:

- (i) Comparison of the measured sag profile of lithographic lens with prescribed lens for lens aperture diameter of 1.3 mm
- (ii) Comparison of the measured sag profile of INGENERIC lens with prescribed design for aperture diameter of 1.5 mm
- (iii) plot showing a qualitative description and comparison of dead transition zone formation between consecutive lenslets in lithographic and INGENERIC MLA

Moreover, in the case of an array of aspherical microlenses, deviations of surface sag especially at the microlens edges can lead to the formation of dead transition zones (flat and shallow interfaces) between consecutive lenslets as shown in Fig.2 (iii).

These dead zones were characterized using a laboratory benchtop imaging setup by NASA whose layout can be seen in Fig. 3(i). Using this setup, white light that passed through a rectangular slit located at the focal plane of the telescope was collimated, and redirected to illuminate the MLA. The MLA generated 16 round images of the telescope exit pupil, which were imaged using a telecentric lens on a SWIR camera. The resulting images showed leakage of 'stray' light from interfacial areas between the lenslets shown in part (a) of Fig. 3(ii) and can be attributed to presence of optical aberrations. In aspherical MLAs, the presence of spherical aberrations and transition zones has the consequence of reduced optical coupling efficiency of light into optical fibers.

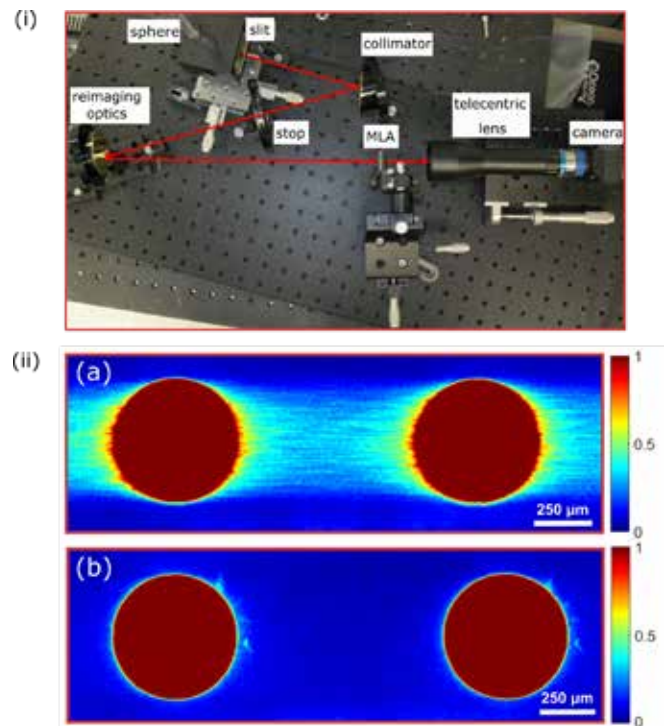


Figure 3:

- (i) Schematic of the benchtop imaging setup used for qualitative analysis of the MLA
- (ii) Camera image showing round profile of images generated by two consecutive lenslets in (a) lithographic MLA and (b) INGENERIC MLA under uniform white light illumination

In search of MLA where the coupling efficiency could be improved, NASA decided to test MLAs fabricated using a precision molding technique. For the second design phase, NASA tested aspherical MLAs from INGENERIC (Fig. 4) with a pitch of 1.5 mm. For this test phase, NASA increased both the lens radius of curvature and array pitch to compensate for changes in instrument layout.

At the beginning of the project, to ensure that the quality of the glass and coating meet the requirements, INGENERIC provided NASA with plane glass samples with a special anti-reflection coating optimized for the entire spectrum from 0.9 to 2.3 μm . Subsequent tests confirmed that the transmissivity requirements were met.



Figure 4:
The microlens array for the NASA PACE mission produced by INGENERIC using the precision molding process.

The next step was to test the accuracy of surface form of produced MLAs and their imaging properties. Using a commercial areal confocal 3D measurement setup (NanoFocus μsurf), the surface profile of the MLA was measured by INGENERIC and compared to the design requirements by NASA. As shown in Fig. 2(ii) a comparison of the two profiles showed an excellent agreement between the design requirements of NASA and the INGENERIC manufactured lens profile. This resulted in the INGENERIC produced MLAs to have transition zones that were almost an order of magnitude smaller than the MLAs produced by lithographic methods! Furthermore, pitch analysis of the INGENERIC MLA showed an exceptional accuracy with pitch errors $<1 \mu\text{m}$.

Furthermore, using the qualitative laboratory bench-top imaging test, NASA observed a considerable decrease in the 'light leakage' areas from the MLA interface (part (b) of Fig. 3(ii)), which again shows a qualitative improvement in the performance of the MLAs. While the previously used etched MLAs from other manufacturers did not meet NASA's requirements, INGENERIC's MLAs significantly exceeded the original expectations.

Both project partners attribute the superior performance of INGENERIC's MLAs to the manufacturing process: Precision molding of aspherical microlenses that enables the design specifications for the shape of the lenses to be met with the highest precision. In this way, the lenses achieve optimum image quality. This is especially true for the edges of neighboring

microlenses when coupling into glass fibers: If they are not manufactured precisely, light is scattered into the transition zones between the fibers and cannot be used for coupling. Here, too, the MLAs from INGENERIC perform impressively.

The current project status

The OCI will be built at the Goddard Space Flight Center in Greenbelt in the American state of Maryland. Laboratory tests are currently being carried out at component level (breadboard) to optimize the mechanical adjustment of the fiber bundles. The next steps will be the connection to the telescope and the examination of the entire optical path from the exit of the telescope to the entrance of the fibers. Integration into the Engineering Test Unit is planned for the summer of 2019. The satellite is expected to enter orbit in 2022.

Summary

During the development of the "Ocean Color Instrument" OCI for NASA's PACE project, microlens arrays from INGENERIC, which the company manufactures using the precision molding process, proved to be far superior to etched arrays: They exceed the original requirements of the customer and will thus contribute to a significantly increased efficiency of coupling the light from the ocean surface into glass fibers of the satellite's optical system.

Precision moldings

INGENERIC works with precision molding techniques, which ensure that high refractive index glass takes on precisely the form of the molding tool. The molds manufactured by the company to sub-micron precision enable the arrays to be produced with exceptionally high accuracy and reproducibility. INGENERIC successfully manufactures arrays with minimal transition zones, highest filling factors and minimal pitch errors, even in large batches.

When it comes to designing micro-optics for special applications, the process offers significant degrees of freedom: Compared to the etching process, optics can be far more complex with a larger radius-to-aperture aspect ratio. Furthermore, the process excels with a relative radius tolerance better than 0.2 percent, which is fully reproducible in serial production.

The array structures typically have dimensions in the sub-millimeter range, and the form accuracy is sub-micrometer at less than P.V. 250 nm. Another advantage is the small transition zone between the lenslets which is typical less than 10 μm . This makes it possible to produce arrays with high fill factors and to make the best possible use of the optically effective surface area. The benefit to the user: Optimal beam shaping and high-efficiency transmission.

Especially for micro-lens arrays for some applications the pitch accuracy is very important. INGENERIC is able to offer also a very high precision: INGENERIC reproduces the separation between the individual lens center points with an accuracy of better than 2 μm over a length of 25 mm, so there is no accumulation of errors across the width of the array.

For some micro-optics-particularly the two-sided structures – the exact adherence to the central thickness is vitally important, since they have a telescopic effect and the slightest deviations lead to aberrations. INGENERIC achieves accuracies in the μm range here.

INGENERIC manufactures microlens arrays with aspherical or spherical lenses that are planoconvex, biconvex or convex-concave, and which have a circular, rectangular or hexagonal aperture.

ABOUT INGENERIC

Founded in 2001 in the university-city of Aachen, Germany, INGENERIC GmbH develops and manufactures high-precision micro-optic components for high-power applications, along with optical and laser systems including fiber couplers, homogenizers and collimation modules for science, medicine and measurement technology.

Today, INGENERIC is one of the few manufacturers in Europe to develop and manufacture glass micro-optics for beam shaping in semiconductor diode lasers according to the individual specifications of its international customers. The company handles the entire process chain from the lens design and the development of prototypes through to the small-batch production and serial manufacture.

INGENERIC GmbH

Zum Carl-Alexander-Park 7
52499 Baesweiler
GERMANY

Phone + 49 2401 804 70400
Fax + 49 2401 804 70499

contact@ingeneric.com
www.ingeneric.com