MICRO-OPTICS IS...

Phabulous

Pilot Line Technology Handbook

Providing highly advanced & robust manufacturing technologies for optical free-form micro-structures

www.phabulousproject.eu

Table of Content

Introducing PHABULOuS 4

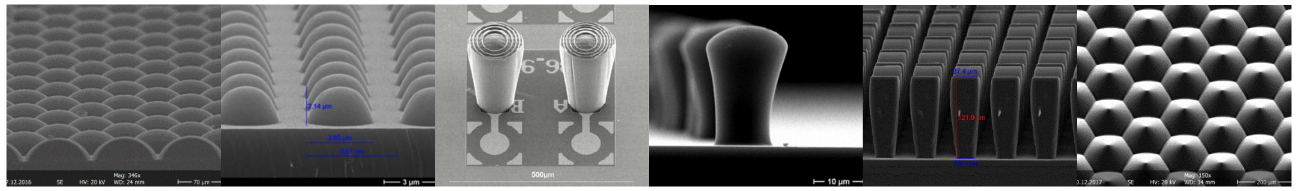
Funded by
PHOTONICS21
PHOTONICS PUBLIC PRIVATE PARTNERSHIP

Introducing PHABULOuS

A new era for free-form micro-optics

Free-form Micro-optics are micro-optical components:

- Designed with no symmetry constraints
- Enabled by innovative modelling
- Requiring ultra-precision machining

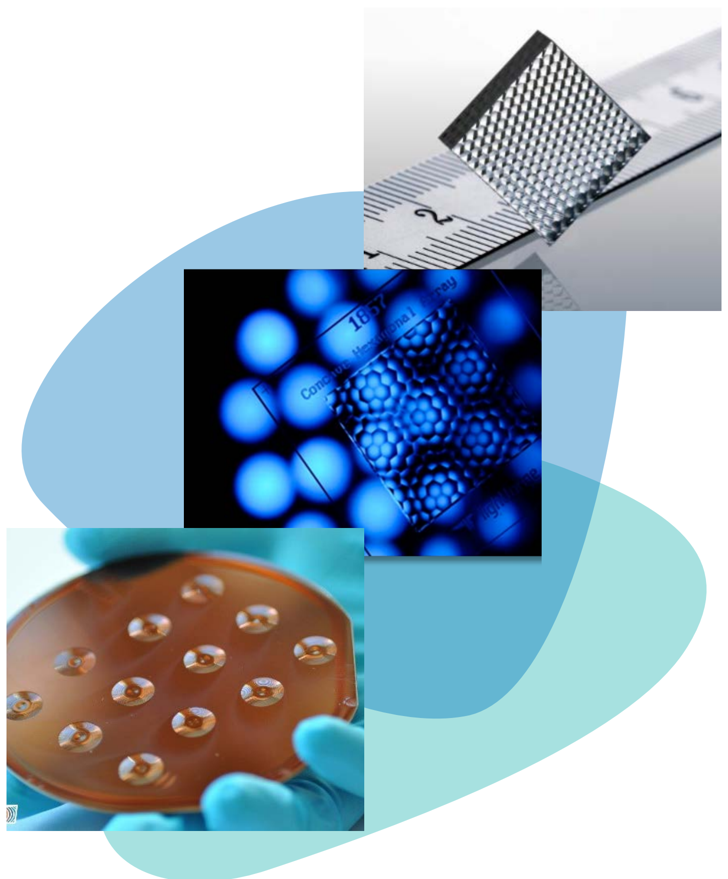


Innovative technology with various advantages

- New functionalities with aberration reduction
- Miniaturization & integration
- Low-weight & Large-area
- Flexibility & Conformability
- Low-cost mass manufacturing
- System simplification

Advanced technology

- Design
- Fabrication
  - Mastering
  - Up-scaling
  - Tooling
  - Replication
- Material
- Characterization
- Mass production
- Integration

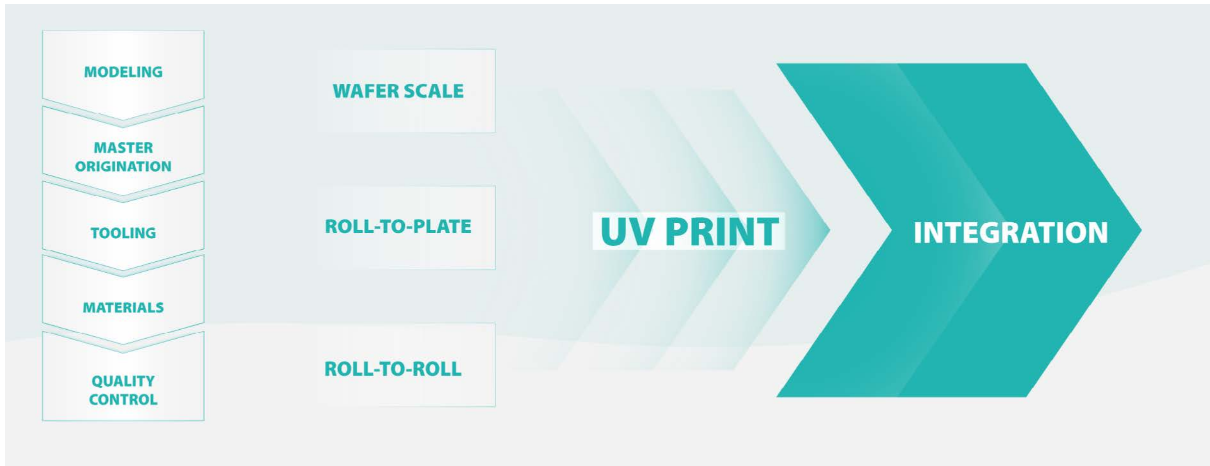


MICRO-OPTICS IS...
Phabulous

Introducing PHABULOuS

Unique selling proposition

PHABULOuS offers a unique **one-stop shop** for all requests for prototyping and manufacturing of free-form micro-optics services: from pilot to full-scale production.



PHABULOuS's goal is the industrial manufacturing of innovative and highly demanded micro-optical components for **various photonics applications**, with a clear roadmap for high volume production in Europe at a competitive cost.

Pilot-Line Association

The Association is established within the framework of the H2020 European research project entitled "Pilot-Line Providing Highly Advanced & Robust Manufacturing Technology for Optical Free-Form Micro-Structures" funded by the European Commission **("PHABULOuS Project")**.

The main objectives of the PHABULOuS Pilot-Line association are:

- Implement the PHABULOuS Project in accordance with the Grant Agreement n°871710
- Unify European research and technology organisations and industrial partners into a Pilot Line for the design and manufacturing of free-form Micro-optics solutions.
- Test the efficiency of the Pilot-Line concept through the validation of requests for piloting services within the implementation of the PHABULOuS Project.
- Promote advanced photonics technologies and solutions and offer a single-entry point (one-stop shop) in order to facilitate access to comprehensive problem-solving competency for the complete production chain, which is intended to continue after the PHABULOuS Project.
- Represent the interests of the PHABULOuS Pilot-Line community on a national and international basis.

The Pilot-Line Front Office (PLFO) of PHABULOuS – An independent legal entity that will provide customers with a single-entry point to the Pilot-Line and its services in Europe, for SMEs and LMEs aiming to pilot and produce devices integrating free-form micro-structures. Contact our front office at info@phabulous.eu.

The PLFO will be responsible for dissemination, advertising, and outreach of the offered manufacturing services. It will create advertising material and will build up the PHABULOuS Pilot-Line corporate identity and design.

Free-form micro-optics industry

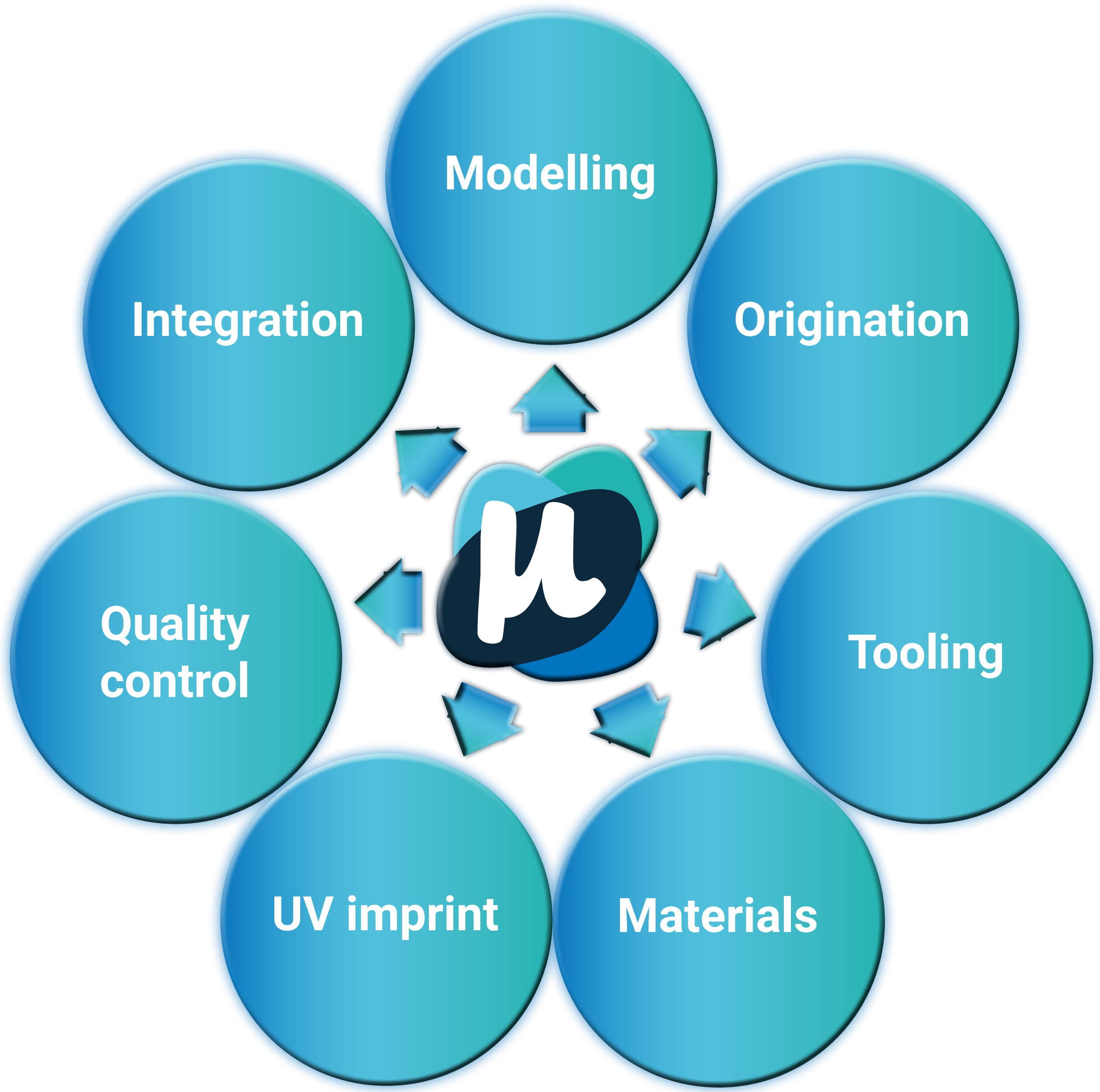
Prototyping ▸ Piloting ▸ Large volume production

- Accelerated innovation & production cycles: From modelling to manufacturing and quality control of free-form micro-optics
- Manufacturing services: Various replication and coating technologies
- Clear roadmap for high volume production at competitive cost

Funded by

MICRO-OPTICS IS...

Introducing PHABULOuS



Funded by

State-of-the-art Technologies

1 - Open design platform

The PHABULOuS Pilot Line aims to support customers from an early stage. With this objective, PHABULOuS will open a design platform where customers will benefit from our proprietary design toolbox.

The PHABULOuS Pilot Line design platform includes proprietary solutions for the design of free-form micro-lens arrays (FMLAs) based on customer specifications. Specifically, PHABULOuS will offer two complementary design approaches.

Indirect design – Using complex arrangements of well-known, manufacturable micro-structures, prescribed illuminance distributions (e.g. non-uniform) can be achieved. Developed for lighting applications, this approach ensures a rapid transition to a successful manufacturing and large integration tolerances.

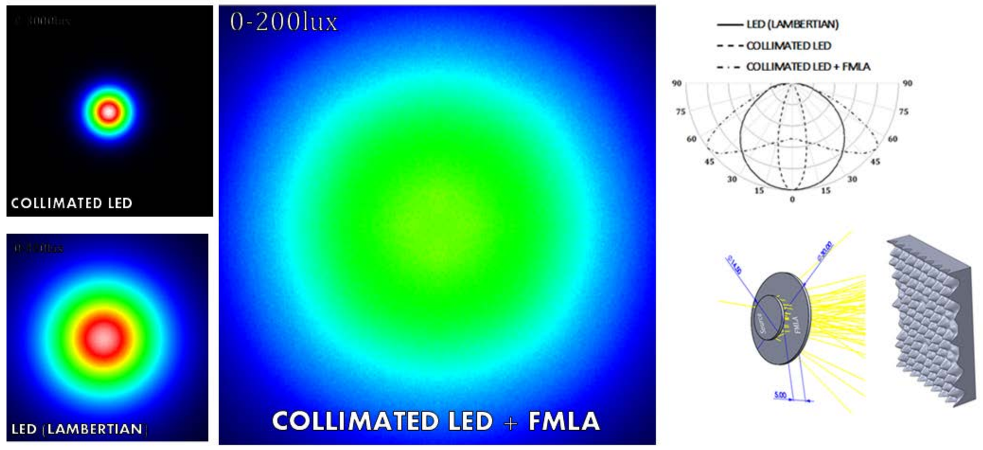


Figure 1: A narrow-beam LED is beam-shaped to a batwing LID (luminous intensity distribution) by a FMLA designed using the indirect design approach. Left) Far-field Illuminance distributions. Right-top) normalized candle-power plots. Right- bottom) ray-traced CAD models of the light source and FMLA.

Direct design (Ray-mapping) – Based on ray-mapping algorithms customized for micro-optical components, this approach is ideal for highly demanding illuminance distributions (e.g. asymmetric) were initial guesses on the micro-lens shape are not available.

MICRO-OPTICS IS...

State-of-the-art Technologies

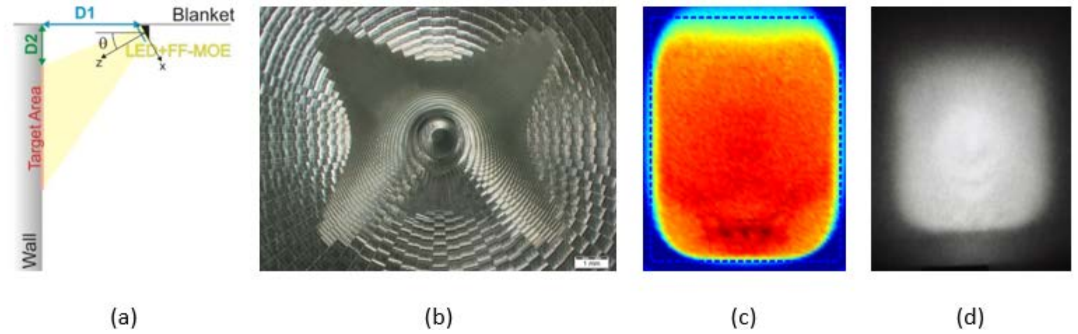


Figure 2: Asymmetric wall-wash lighting solution designed using the direct design approach. a) Schematic illustration of the optical system. An LED light source on the ceiling should homogeneously illuminate an oval target area on the wall. b) Designed the FMLA. c) and d) Predicted and measured illuminance distribution on the target area.

Design for manufacturing – The PHABULOuS design toolbox comprises commercial design and simulation software tool such as ZEMAX, LightTools, LucidShape, Light Trans, FRED etc. coupled to enabling CAD modelling solutions (SolidWorks, CATIA, AutoCAD, Rhinoceros & Grasshopper, Resurf, etc.) and custom-made scripts (Python, MATLAB, etc.). With this toolbox, the PHABULOuS design offer will be completed with design-for-manufacturing kits that will enable customers to:

- Provide their optical designs in the most common representation formats including point clouds, STL, IGES, STEP, and Polynomials.
- Validate their optical designs for manufacturability and select the most appropriate manufacturing technology.
- Quantify expected manufacturing deviations and predict performance degradation hence avoiding costly trial-error cycles.
- Provide design rules to fine tune the initial optical designs towards a successful production and a satisfactory optical performance.

.

State-of-the-art Technologies

2 - Origination: form accuracy & surface quality

PHABULOuS innovative technological offer – The large scope of applications targeted by PHABULOuS translates into a wide range of FMLA geometries and dimensions, tolerance levels and form accuracy and surface quality specifications. In order to broaden its technological offer, the PHABULOuS Pilot Line offers an extensive selection of origination technologies including additive and subtractive, mechanical and laser-assisted, mask-based and maskless. Specifically, the PHABULOuS Pilot Line currently offers diamond and laser micro-machining, two-photon absorption, maskless grey-scale lithography, fs-laser ablation, and photo-lithography/Si-etching.

Figure 3: MLA, FMLAs, and 3D nano-structures fabricated using a) DMM, b) LMM, c) FSLA, d) GSLL and e) LMP-TPA.

Diamond Micro-Machining (DMM) with demonstrated sub-micron form accuracy and nanometre surface quality is ideal for optical applications. (On-axis) diamond turning is especially well-suited for the manufacturing of micro-lens arrays but relies on the manual shifting of the workpiece. This is impractical for large micro-structure arrays due to the poor position accuracy, large balancing errors and long processing times.

Dynamic Part Indexing (DPI™), a patented technology available in PHABULOuS is an add-on to an ultra-precision diamond turning lathe that alleviates the mentioned limitations. DPI enables the automatic shift of the substrate for an efficient on-axis diamond turning of large lens arrays comprised of aspheres, freeforms or even diffractive optical elements. The table on the right compares DPI™ to three well-known free-form machining technologies namely Slow Slide Servo (SSS), Fast Tool Servo (FTS) and Diamond Micro-Milling (DMM). Further improvements of DPI™ will allow to achieve submicron positioning accuracy over large lens arrays or masters up to 8 inches.

	SSS	FTS	DMM	DPI™
Maximum slopes (o)	20	20	45	80
Process speed	-	+	- -	+
Form accuracy (pv; in nm)	300	600	300	100
Roughness (Ra; in nm)	10	10	10	2
Ultrasonic turning	N	N	N	Y
Grinding	N	N	N	Y

MICRO-OPTICS IS...
Phabulous

State-of-the-art Technologies

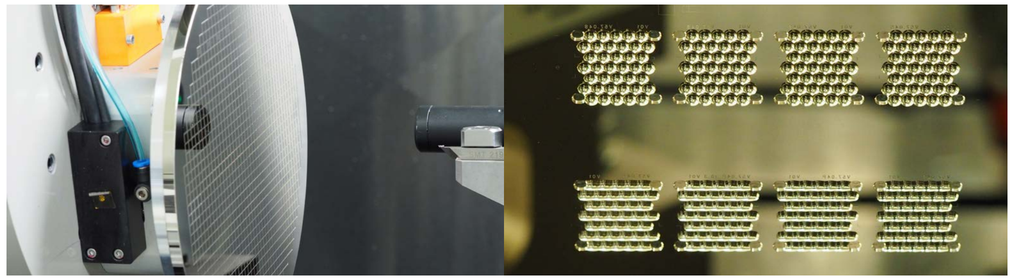


Figure 4: Diamond micro-turning: Dynamic Part Indexing (DPI™) for Micro lens arrays (MLAs). Left) 8" prototype MLA wafer. Right) Close-up view of machined FMLAs on a 8" wafer.

Laser Micro-Machining (LMM) is a direct-write micro-machining technology compatible with the manufacturing of fully free-form micro-optical components in fused silica in short time scales.

Laer Micro-Machining does not require product-specific hard tooling (such as moulds or photo-masks) and it hence ideal for rapid prototyping with low-cost design iteration. The sub-micron form accuracy and excellent surface quality (nanometre surface roughness) demonstrated by PHABULOuS. LMM makes it very attractive as an origination process for large-volume UV-imprinting replication.

The Laser Micro-Machining equipment available in PHABULOuS is highly automated on (4" maximum) wafer-scale with a throughput of ~ 1 cm²/h (for 100 µm height) and can currently produce free-form micro-structures with in-plane sizes of up to 100 µm, structure heights in the (5-250) µm range and up to 30° slope angles.

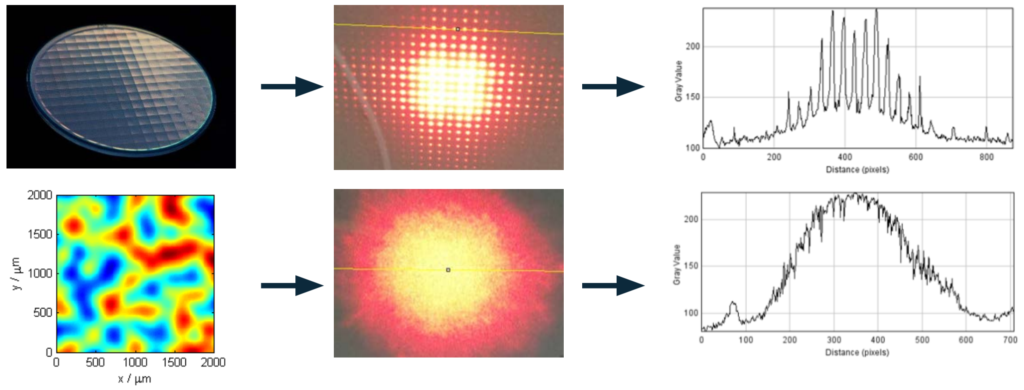


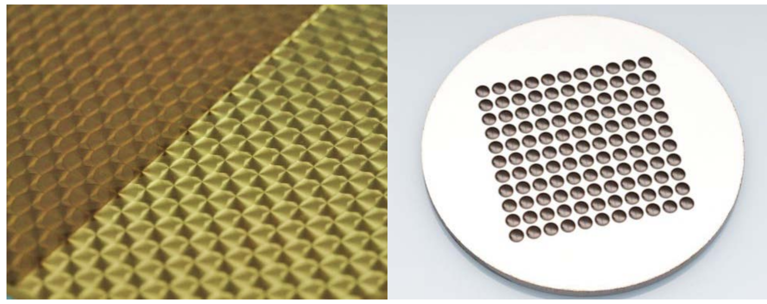
Figure 5: Laser micro-machined FMLAs (PRIME Beam-shapers). Top) Lens Array with Low M2 Beam. Bottom) PRIME with Low M2 Beam).

State-of-the-art Technologies

Two-Photon Absorption (TPA) enables full three-dimensional structuring of arbitrarily complex models with a resolution in the submicron range. Although well-established on a laboratory scale, industrial level throughput has not been demonstrated yet.

Greyscale laser lithography (GSLL) is compatible with the origination of FMLAs with optical quality surfaces. The key features have a minimum lateral feature size of 200 nm, a maximum structure height of around 50 µm (aspect ratio of 1:4) with an accuracy of 80-85%.

Femtosecond laser ablation (FSLA) enables fast and contactless machining of embossed designs with perfectly monitored dimensions This technique demonstrated highly asymmetrical shapes on many different substrate materials.



Polished « Perlage » (Gold) Micro cavities (Stainless steel)

Figure 6: Example of micro-structures originated with FSLA technology on 1 cm diameter stainless steel substrate (LASEA).

Photo-lithography and Si-etch (Si-E) – PHABULOuS offers a unique photo-lithography portfolio in combination with appropriate dry or wet etching capabilities to support the origination needs: depending on the requirements, very specific and designed Free-form structure will be originated from either a standard 193 nm optical lithography, and/or using Maskless lithography (ML2) and/or Direct Self Assembly (DSA) and/or (nano) imprint and/or combination of these options. For that purpose, a standard 2D shape is first achieved by photo-lithography and subsequently transferred to the final substate via etching to obtain the desired 3D FMLA structure.

Funded by

State-of-the-art Technologies

PHABULOuS ambition – The PHABULOuS Pilot Line is currently (and will continue to) committing considerable efforts to accelerate all the origination technologies Beyond the State of the Art. Our ambition is summarized in the table below.

Technology	PHABULOuS ambition (Beyond state-of-the-art)
Diamond micro-machining	Increased throughput by a **factor of 3** (indexing time reduction **from 15 to 5 seconds**) Increase maximum slope angles **from 45 up to 60°** (with metrology) Improve lens positioning accuracy over large lens arrays or masters **down to 1 µm**
Laser micro-machining	Increase throughput by a **factor of 2** Increase clear aperture **from 2 to 4 inch** Increase maximum angles **from 30° to 60°** (with metrology) Increase maximum lateral dimensions **from 100 to 250 µm**
Femto-second laser ablation	Increase writing resolution **from 2 µm to 1 µm** Reduce surface roughness, from several **100's nm down to 10 nm (RMS)**
Greyscale laser lithography	Maximum height increased **from 50 µm up to 150 µm** Lateral dimensions **between 0.4 - 500 µm** Form accuracy increased **from 80% to 95%** Single optical element size (lateral) **between 5-500 mm**
Two-photon absorption	Increase manufacturing throughput by a **factor of 5** Increase scanning speed by a **factor of 10** Reduce surface roughness, **from 10's nm down to 10 nm (RMS)** Lateral vertical dimensions **between 0.1 - 500 µm (5-100 µm)**

Optical components require high accuracy (sub-micron) manufacturing to ensure compliance with customer specifications. FMLAs optical designs often comprise angular and linear dimensions largely dissimilar making accurate manufacturing extremely challenging, time consuming and expensive. Moreover, the origination time and cost increases (nearly) quadratically with increasing area, a limitation for large-area applications. The PHABULOuS Pilot Line addresses this limitation by complementing the previously described origination technologies with upscaling, tooling, and large-area UV imprint replication technologies described in the following sections.

Funded by

3 - Upscaling and Tooling

Upscaling for UV imprint replication – In analogy with optical lithography steppers, the so-called UV imprint step-and-repeat (S&R) technology enables the up-scaling of small masters to large-area tools for subsequent large-area replication thus keeping the origination effort limited to small areas and affordable cost.

Large-area applications often **demand for seamless working masters/ tools** where the adjacent FMLAs are precisely positioned in contact to one another, i.e. with negligible gaps or alternatively with well-controlled slight overlapping.

PHABULOμS S&R technology has demonstrated 20-50 μm stitching accuracy (gap or overlapping). The ambition is to reduce this figure down to 1-5 μm, which corresponds to 1-10% of the typical lateral dimensions of the FMLA features.

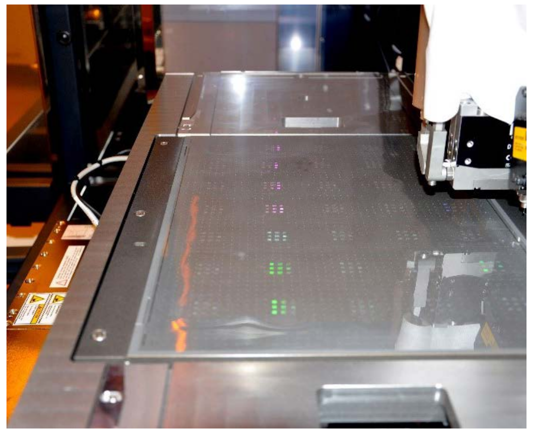


Figure 7: Production of flexible embossing tools for roll-based UV imprint replication.

For roll-based replication specific tools need to be manufactured. Depending on the replication technology, we offer:

Tool production for R2P UV imprint replication (Large-area soft stamps) – Tool up-scaling is also achievable by tiling multiple small-area masters on a large-area flexible stamp.

Tool production for R2R UV imprint replication (Electro-formed Nickel shims) – A galvanic electroplating process is used to transfer micro-structured surface of the up-scaled master onto a robust (but flexible) replication tool (Nickel shim) for subsequent high-throughput and cost-effective wafer-scale or roll-to-roll (R2R) UV imprint replication.

Funded by
PHOTONICS21
PHOTONICS PUBLIC PRIVATE PARTNERSHIP

MICRO-OPTICS IS...
Phabulous

State-of-the-art Technologies

Main advantages of PHABULOuS up-scaling and tooling technologies		
Step-and-repeat (S&R)	**Large-area soft stamps**	**Electro-formed Nickel shims**
Cost-effective	The large-area flex stamp can be re-used over 500 to 1000 times, and is thereby highly cost-effective.	Cost-effective and reproducible replication of master with minimal quality variation. A high number of nickel tools can be manufactured from a single master.
Industry-compatible	The possibility to tile multiple products on the large-area soft stamp enables high-volume production volumes.	High resolution and good replication fidelity.
Step & Repeat imprint method has accurate positioning within 5 μm	Roll-to-Plate imprint alignment accuracy from large-area soft stamp to substrate is well below 100 μm. Developments ongoing for industry-compatible soft-stamp to substrate alignment accuracies of below 10 μm.	Good mechanical durability and chemical resistance of the tool.
Flexible	The Roll-to-Plate imprint technology is flexible; the large-area soft stamp can be changed easily in few minutes, imprinting same or a different nano or micron-structure.	Chemical modifications of the nickel replication reel for extension of the reel lifetime. Cleaning of the nickel tool can further extend the tool lifetime.

The ambition of PHABULOuS is to produce replication tools with areas up to 200 mm round for wafer-scale, 600×1000 mm^2 and up to 1100x1300 mm^2 for Roll- to-Plate (R2P), and 450×450 mm^2 for Roll-to-Roll (R2R) with a stitch width and height below 5 and 10 μm, respectively, using a S&R approach and to increase tool lifetime by at least 80% through the development of new handling/cleaning and packaging/transport procedures.

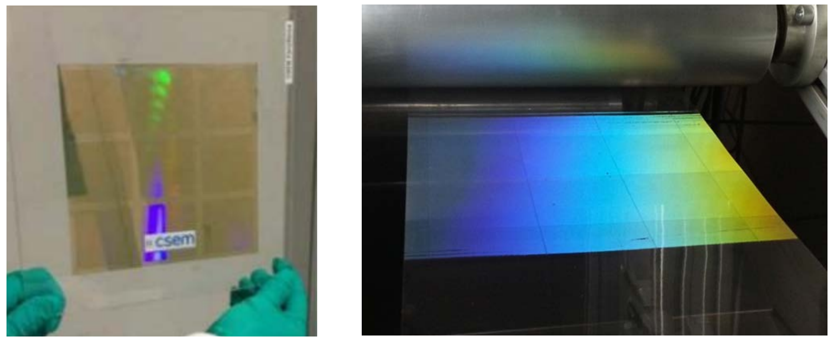
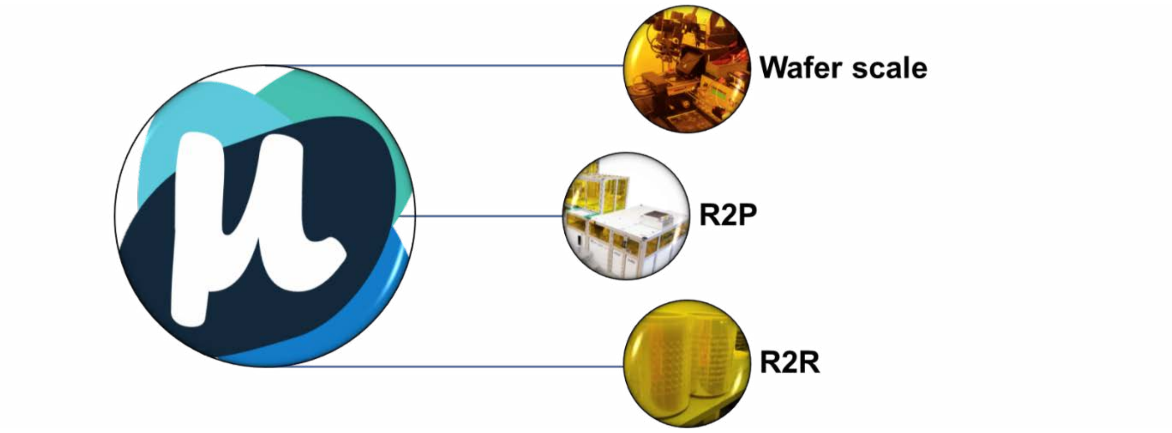


Figure 8: Left) Plasmonic gold nano-structures fabricated with a step-and-repeat UV casting process, resulting in a 15x15 cm^2 sample. Right) Sheet with a 2D diffractive nano structure for enhanced in coupling for thin film photovoltaics.

Funded by
PHOTONICS21
PHOTONICS PUBLIC PRIVATE PARTNERSHIP

4 - Large-area UV imprint replication

PHABULOuS provides three different technologies for the cost-effective, high-throughput large-area UV imprint replication technologies. The table below summarizes the ambitioned maximum area and capacity.



Replication pillar / Property	Wafer scale	Roll-to-Plate (R2P)	Roll-to-Roll (R2R)
Maximum surface area (others)	200 mm diameter	1100x1300 mm^2 plates	500mm web width* (production line) 240 mm (R&D line)
Maximum surface area in PHABULOuS	300 mm diameter**	550x650 mm^2 and up to 1100x1600 mm^2 plates	500 mm web width* (production line) 240 mm (R&D line)
Yearly capacity (others)	10000 wafers	4000 plates***	1500 km/line (production line) 200 km/line (R&D line)
Yearly capacity in PHABULOuS	30000 wafers**	2000 plates	200 km/line (production line) 25 km/line (R&D line)

**480mm micro-structured width; ** With the production ramp-up planned by PHABULOμS partner SUSS Micro-optics (Excellence Center);*
****Up to 250000 plates possible depending on equipment used*

UV imprint replication of FMLAs with sub-micron form accuracy – UV imprint replication is an extremely promising technology for the low-cost and high throughput replication of complex 3D micro and nano-structures with ultra-high precision. The recent development of large-area UV imprint processes has enabled the mass manufacturing of large-area micro/nano-structures thereby enabling new commercial applications.

Wafer-scale UV imprint replication comes with key features such as layer-to-layer alignment and front-to-back alignment and multi-stacking capabilities. On the other hand, it enables complex processes such as wafer-level packaging and direct connection to optoelectronic components.

Combining this technology with free-form optics addresses new markets (such as AR/VR, automotive lighting, CMOS imager and displays) which demand for high performance, low cost, and compactness. The technology is already available and running in high volume for the automotive market, but is not yet applied to FMLAs.

Main advantages of PHABULOuS Wafer-scale UV imprint replication technology	
Maximum structures height	500 µm
Minimum residual layer thickness	≈ 20 µm
High alignment accuracy of components	3 µm in wafer plane and 10 µm normal to waver plane
Various lens materials	Hybrid sol-gels (solvent free) and Epoxies
Process on	Wafer up to 200 mm diameter (upgrading to 300 mm diameter)
Form accuracy of structures / optical quality of surfaces	< 20 nm rms

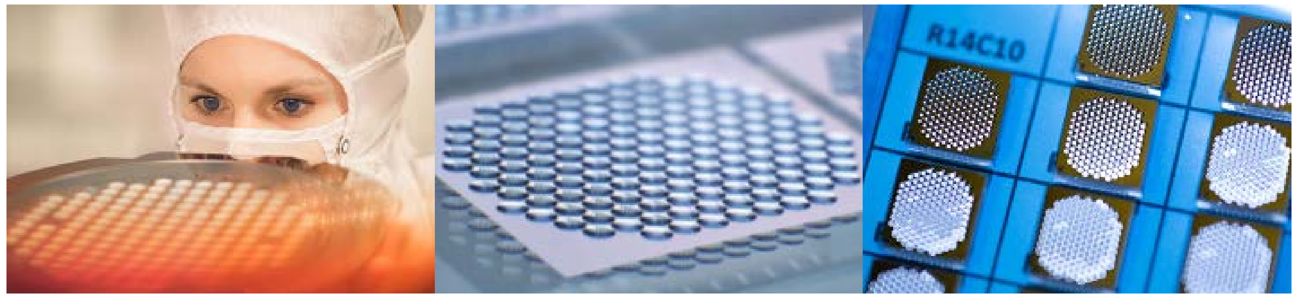


Figure 9: Micro-imprint fabrication of micro-optical elements. Micro-optics is fabricated on wafers of 200 mm diameter and separated by dicing. Each micro-optical element has more than 100 channels to realize its functionality. The multichannel concept together with free-form optical design allows to realize illumination and imaging of objects with extraordinary homogeneity and no deformation.

State-of-the-art Technologies

Roll-to-Plate (R2P) UV imprint replication technology focuses on three fundamental aspects namely the technology scalability, cost effectiveness (large area & high volume) and compatibility with available production lines. Currently there are many proven processes for textures well below 100 µm height, shrinkage around 5% and industry-compatible manufacturing yields that are highly design dependent.

Main advantages of PHABULOuS R2P UV imprint replication technology:

- Provide their optical designs in the most common representation formats including point clouds, STL, IGES, STEP, and Polynomials.
- Validate their optical designs for manufacturability and select the most appropriate manufacturing technology.
- Quantify expected manufacturing deviations and predict performance degradation hence avoiding costly trial-error cycles.
- Provide design rules to fine tune the initial optical designs towards a successful production and a satisfactory optical performance.

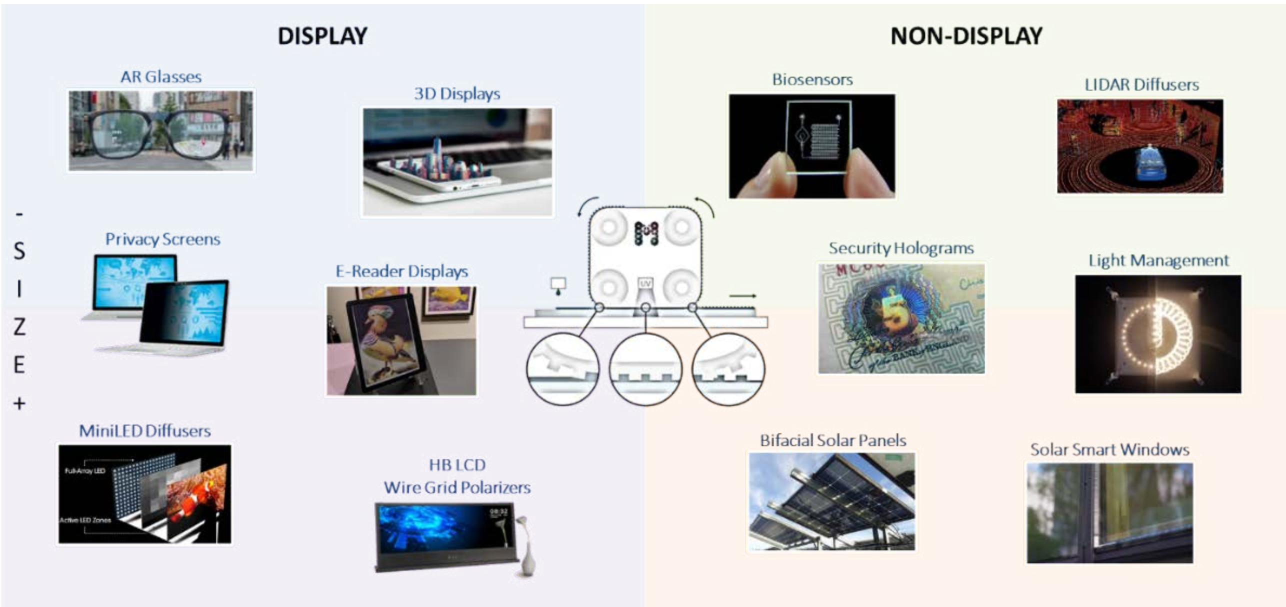


Figure 10: The R2P technology can be used for different applications where precise micron or nano-scale structures are need at high volume and commercially viable costs.

Funded by
PHOTONICS21
PHOTONICS PUBLIC PRIVATE PARTNERSHIP

State-of-the-art Technologies

Roll-to-Roll (R2R) UV imprint replication is a high-resolution fabrication method, which is characterized by a high throughput and cost-effectiveness. In the continuous R2R replication process, an UV curable resin is used to replicate the desired structures from a cylindrical tool to a flexible substrate. It has been utilized in the mass-production of optical components, including light guides, diffractive optical elements and microlens arrays. R2R UV imprint replication has demonstrated the replication of high-resolution micro and nano-structures with length scales far below those associated with the traditional manufacturing technologies of plastics (e.g. injection moulding). A detailed comparison between R2R UV imprint and two common competing replication technologies is presented in the table on the next page.

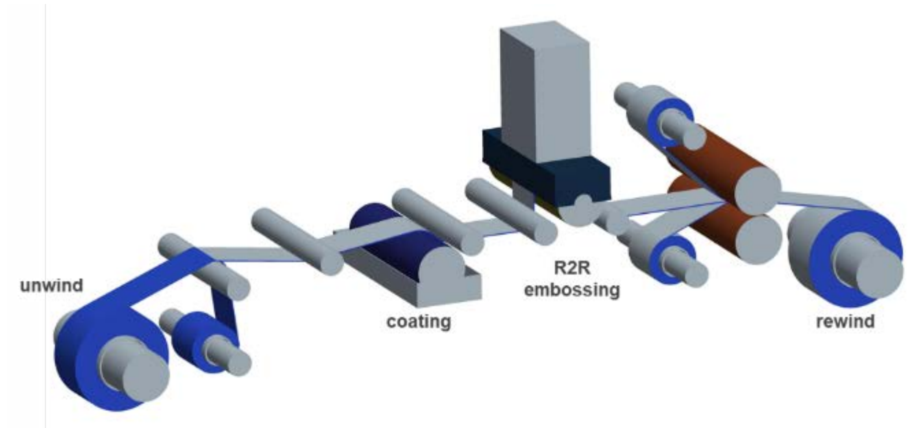


Figure 11: A schematic presentation of the R2R UV imprint process (Nanocomp).

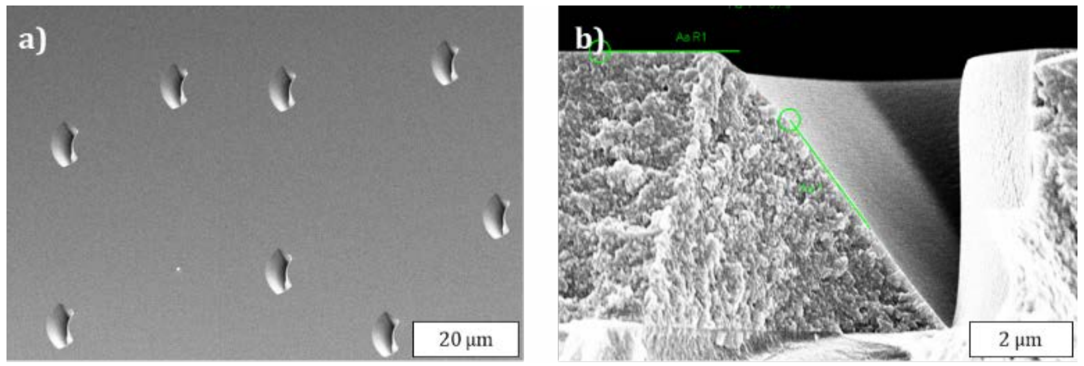


Figure 12: Top view (a) and X-section (b) SEM images of prismatic micro-structures replicated using PHABULOuS R2R UV imprint (Nanocomp)

Funded by
PHOTONICS21
PHOTONICS PUBLIC PRIVATE PARTNERSHIP

State-of-the-art Technologies

Technology	Advantages	Disadvantages
Injection moulding	High speed, automated production Standardized materials Solvent-free process No post-processing needed	High tooling cost No thin-film compatible Limited aspect ratio Low resolution (incomplete mould filling)
R2R Hot embossing	High speed and low cost Standardized materials Thin-film compatible Solvent-free process	Limited optical properties (raw materials) High temperature and pressure process Requires post-processing (cutting)
R2R UV imprint	High resolution and aspect ratio High replication fidelity at high/moderate speeds Tailor-able mechanical, chemical and optical properties of the UV resins Thin-film compatible Room temperature and low-pressure process Solvent-free/solvent-based process Single-step lamination and coating of samples possible	Requires post-processing (cutting) Challenging de-moulding for high aspect ration micro/nano-structures

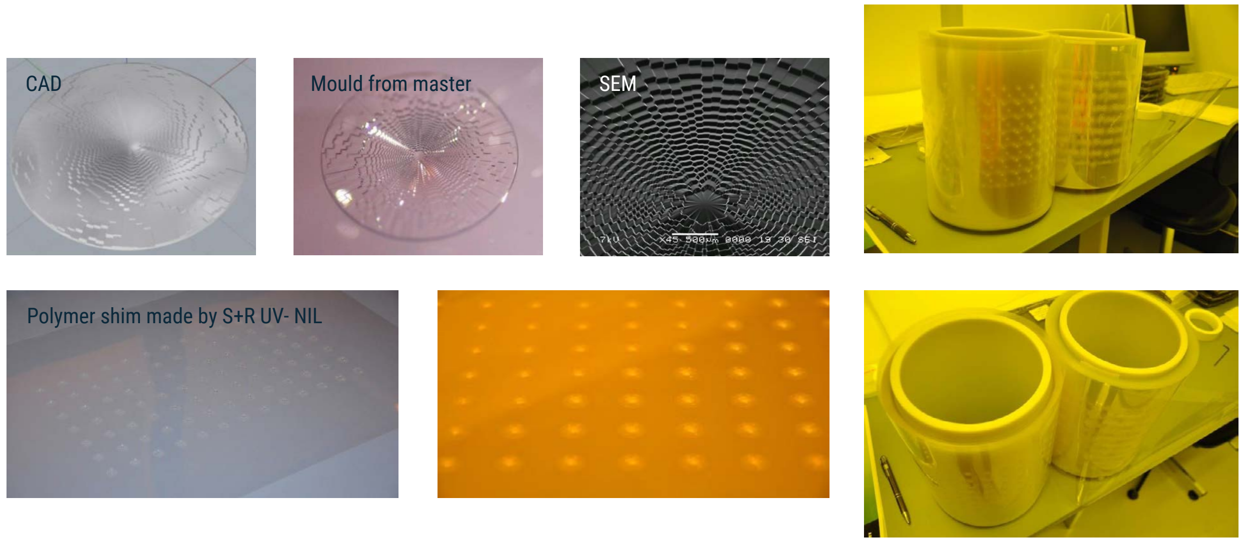


Figure 13: Mastering and replication of FMLAs by JOANNEUM Research Institute

Funded by
PHOTONICS21
PHOTONICS PUBLIC PRIVATE PARTNERSHIP

MICRO-OPTICS IS...
Phabulous

State-of-the-art Technologies

Replication Technology	PHABULOuS ambition (Beyond state-of-the-art)

Wafer scale	Wafer-scale UV imprinting of free-form micro-optics featuring:
	• Profile height:
	  • Range 1: 0–100 µm (± 2%)
	  • Range 2: 100–500 µm (± 5%)
	• Grid overlay accuracy on 8” wafer: ±1 µm on full wafer
	• Front to backside overlay: ±3 µm
	• Absolute form accuracy from lens-like free-form elements
	  • Range 1: ±1 µm (RMS)
	  • Range 2: ±5 µm (RMS)

Roll to Plate (R2P)	Currently there are many proven processes for textures well below 100 µm height, shrinkage around 5% and industry-compatible manufacturing yields that are highly design dependent. Within PHABULOuS we want to demonstrate the R2P UV imprinting of free-form micro-optical textures with: • Material development for shrinkage below 4% • Large-area imprinting (up to 600 mm wide, length of 1 m feasible) • Imprint alignment below ±100 µm • 2-up and/or 4-up tiled replication for high-volume production. • Texture Height (Depth H) > 200 µm (the ambition is H > 500 µm) • Pattern fidelity >90% • Process Yield >90% (product within spec, no air entrapment, no process defects)
Roll to roll (R2R)	The state-of-the-art UV-roll to roll processes are commonly limited up to 10–20 µm standard micro-optical structure (MLA and micro prism) replication to the one-sided polymer film. PHABULOuS pilot line target for the R2R-UV-imprinting of free-form micro-optical structures with: • Height / Depth H >50 µm (the target range is 1< H < 100/150 µm) • Yield >90 % (stemming from defect density <10 %) over 250 mm web width • Pattern fidelity >90% • Double-side UV imprint replication • Replication speed >1 m/min (target: 10 m/min) for throughput increase and cost reduction • Replication length >500 m to demonstrate process reliability and reproducibility

Funded by
PHOTONICS21
PHOTONICS PUBLIC PRIVATE PARTNERSHIP

5 - UV imprint materials

Micro-optical applications impose a plethora of optical and mechanical specifications including high imprint fidelity, high optical transparency, tunable/controllable refractive index and typically low optical dispersion for minimizing chromatic aberration. UV-curable materials suitable for replication of optical micro-structures have moderate refractive indexes in the range of n~1.5.

The versatility of the UV embossing process associated to the possibility to adjust the optical properties **can open new perspectives for optical design**.

The PHABULOuS Pilot-Line will be supplied with a complete palette of low to high refractive index **UV-curable materials to compensate for limitations in the manufacturable curvatures and unlock the potential of FMLAs for various applications**.

In addition, the specific material composition for arbitrary use cases will be developed to fulfil the appropriate standards (i.e. low cost, high-throughput, large-area replication).

The PHABULOuS ambition is to **formulate novel UV-casting materials** with finely-tuned properties as summarized in the table below.

Funded by

PHOTONICS21
PHOTONICS PUBLIC PRIVATE PARTNERSHIP

Optical properties	
Tunable refractive index (1.4 - 1.8 with ± 0.001 precision)	Resin-substrate optical match Strong light bending at moderate surface curvature
Optical quality surfaces (RMS ≤ 10 nm)	Prevent undesired light scattering, thus degradation of the optical function (e.g. stray-light glare)
High UV-light & weather resistance	Long-lived outdoor devices (e.g. PV and daylighting)

Mechanical properties	
Adhesion to substrate (PC, PET, PEN, Glass, Silicon, etc.)	Device robustness and safe de-moulding
Tunable viscosity	Wet layer thickness's from 1 to 100 µm
Shrinkage upon UV-curing (< 5%)	High pattern fidelity (90%)
Tunable elasticity	High scratching resistance and improved flexibility
Tunable surface energy (20 – 70 mN/m)	Defect-free de-moulding

Funded by

PHOTONICS21
PHOTONICS PUBLIC PRIVATE PARTNERSHIP

6 - Thin-film coating

Optical coatings on FMLA structured surfaces are desired either for high reflection (e.g. in decorative application) or as anti-reflection (AR) solutions. Maintaining a homogeneous coating thickness is fundamental to achieve the required optical performance but very challenging, specially over large areas.

PHABULOuS aims at providing integrated services for optical coatings on FMLA structured surfaces for the three UV imprint replication technologies (wafer, R2P, R2R). With this objective, the PHABULOμS Pilot Line will offer the following coating technologies.

Pulsed magnetron sputtering – A set of universal adapted pulsed magnetron sputtering process parameters for high-aspect ratio FLMA polymer surfaces will eliminate the need for multiple pre-test iterations for each structure.

Magnetron sputtering - Using both planar and cylindrical targets and a broad variety of plasma modes such as e.g. unipolar (DC, DC pulsed) or bipolar (Sinus, square wave, Pulse-Package modes) as well as a broad variety of target materials including metals (Si, Ti, Ta, Nb, Sn, Ag, Zr, …) and their oxides and nitrides, as well as transparent conductive oxides (e.g. ITO, AZO, …).

Magnetron PECVD – Silicon-organic precursor monomers are introduced into the sputtering source to achieve organic-inorganic hybrid coatings for mechanically adapted coatings for flexible applications.

POLAR process – Anti-reflective nano-structures are manufactured on uncoated polymer surfaces using a reactive plasma etching process with a dual magnetron as plasma source. The special features of the structure formation may vary in dependence on both the plasma parameters and the type of polymer. The treatment results in a clear reduction of reflectance as well as the corresponding increase of transmittance.

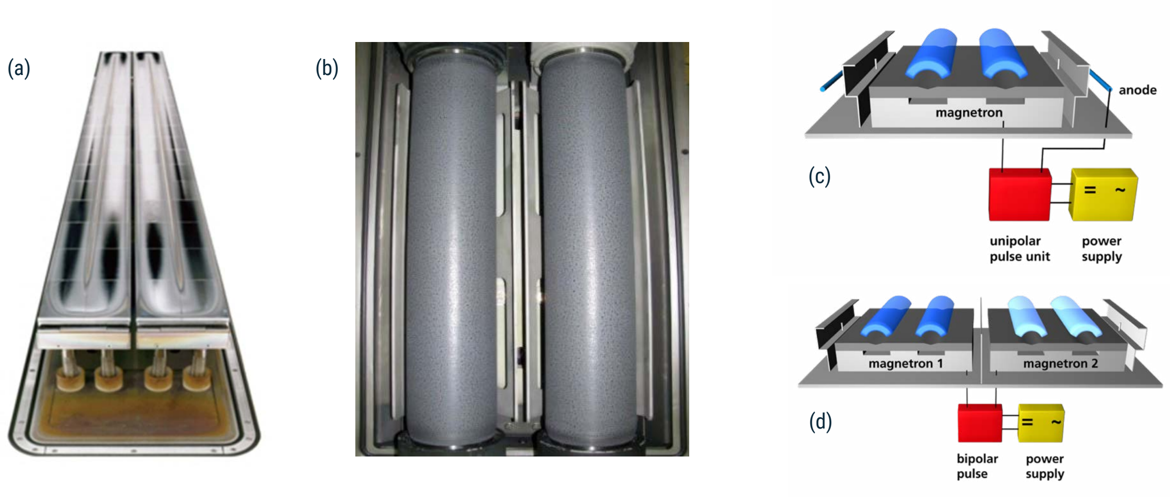


Figure 14: Planar (a) and cylindrical (b) sputtering targets. c) unipolar and (d) bipolar.

Single-run large area plasma surface treatment at 2 m/min (R2R or moving plates) compatible with <1% residual reflection of the FMLA surfaces.

PHABULOuS holds the capacity for pilot manufacturing on 8-inch wafers, 1000×600 mm² plates and rolls with a width of up to 600 mm and a length up to 500 m.

PHABULOuS holistic service portfolio for optics products combines material and stack design, customer-adapted process development for both highly productive and high precision coatings, pilot-scale material provision as well as key components for industrial scale thin film coating.

It is the ambition of PHABULOuS to offer the mentioned technologies in sheet-to-sheet and roll-to-roll configurations to support all customer and applications.

PHABULOuS offer of optical coatings:

Sheet-to-sheet	
Processes	Reactive magnetron Sputtering Magnetron PECVD Reactive polymer surface etching for Anti-Reflection
Multilayer coatings	Anti-reflective coatings Optical filter designs High-reflection coatings
Materials	Metals: Si, Ti, Ta, Nb, Sn, Ag, Zr, … Oxides and Nitrides Transparent Conductors: ITO, AZO, etc.

Roll-to-Roll	
Processes	Reactive magnetron Sputtering Reactive polymer surface etching for Anti-Reflection (for many polymers) High Rate PECVD of SiO_xC_y High-rate evaporation of metal layers
Optical Inline Control	Inline-Spectrometer (cross web Homogeneity of Transmission / Reflection) Hyper Spectral Surface Defect Imaging (starting from Oct. 2021)

7 - Quality control

In order to ensure high quality FMLA components, the PHABULOuS Pilot Line will implement **in-line and off-line quality control process** across the complete manufacturing chain i.e. master origination, tool production and UV imprint replication. The quality of the masters, tools and UV imprint replicas will be quantified using novel characterization methods developed by the PHABULOuS Pilot-Line to overcome the limitations of current state-of-the-art quality control.

The PHABULOuS ambition is to optimize the metrology procedure for quick and accurate quality assessment of the manufactured FMLAs. Specifically, we aim to:

- Quickly (>1 cm^2/h) measure the microscopic surface profiles of **up to 500 µm** height with lateral, and vertical resolution below 300 and 50nm respectively and surface slopes **>60°**.
- Perform automatic side-by-side comparisons of designed and measured profiles with **sub-micron** resolution to determine manufacturing limits and quantify progress on tooling and replication
- Translate manufacturing inaccuracies into optical performance degradation by performing ray-tracing simulation from the measured profiles and simulating the true optical performance with an **over 95% accuracy,** thereby offering a genuine quality check, thus de-risking customer decisions.
- Establish non-destructive quality control procedures based on state-of-the-art methodology to detect surface defects on large (≥0.3×1 m^2) (free-form) micro-structured optical surfaces and rolls within two days after production.

PHABULOuS characterization methods	
Surface profilometry	Tactile, confocal and white-light interferometry surface profilers Optical Microscopes Atomic force microscopy Field-Emission SEM Surface + Cross-section Imaging
Large Area Surface Inspection	ISRAVISION roll-to-roll surface inspection (300 mm width) Roll-to-Roll monitoring of Transmission and Reflection
Optical Properties	UV-VIS-NIR spectrophotometer with Integration sphere VN-accessory for measurement of absolute reflectance FT-IR-spectrometer in transmittance, reflectance & ATR Haze and gloss measuring Spectroscopic ellipsometry
Material Robustness, reliability, and ageing	Bending and rolling tester with minimum of 1.5 cm bending radius Linear Strain tests (up to 150°C) Outdoor weathering test station Climate chamber for damp-heat-test & temperature-cycle-test Condensation water test and salt spray test Abrasion-Tests: (1) Pencil test; (2) Sand Tickling Test; (3) Taber Abraser
Chemical composition	Element analyses with x-ray fluorescence or EDS or GD-OES

Funded by
PHOTONICS21
PHOTONICS PUBLIC PRIVATE PARTNERSHIP

MICRO-OPTICS IS...
Phabulous

State-of-the-art Technologies

Surface profilometry – The optical response of optical components is strongly determined by their surface profile. In comparison to standard spherical and aspherical optical micro-lenses and micro-lens arrays, MLAs, free-form micro-lens arrays, FMLAs are characterized by more complex geometries such as asymmetrical surface profiles, large aspect ratios, steep angles, etc. that need to be accurately measured.

The PHABULOuS Pilot-Line offers a wide portfolio of State-of-the-art surface analysis characterization tools (see first column in the table above). Their capability to accurately measure complex geometrical features will be quantified and a portfolio / catalogue of relevant solutions and characterization protocols / sequences derived for different types of optical (free-form) micro-structures.

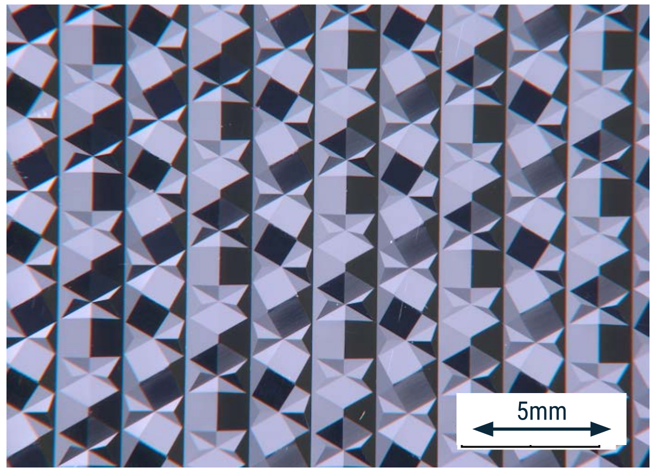


Figure 15: Left) bending/rolling characterization. Right) microscope picture of a FMLA

Funded by
PHOTONICS21
PHOTONICS PUBLIC PRIVATE PARTNERSHIP

State-of-the-art Technologies

Surface analysis – The presence of thousands to millions (large data sets) of complexly shaped (wide parameter space) individual micro-structures present on each FMLA component makes their quality control a real challenge even when using appropriate surface profilometers.

In order to alleviate this, PHABULOuS uses the recently developed so-called **"semi - empirical characterization method"** (see figure 16), which enables the effective quality control of manufactured FMLA components with complex surface geometries with respect to the customer specifications. This method will be improved for higher efficiency and accuracy. In addition, The PHABULOμS Pilot-Line will develop effective CAD methods to compare large point clouds (measured surface profiles) and CAD files (nominal designs).

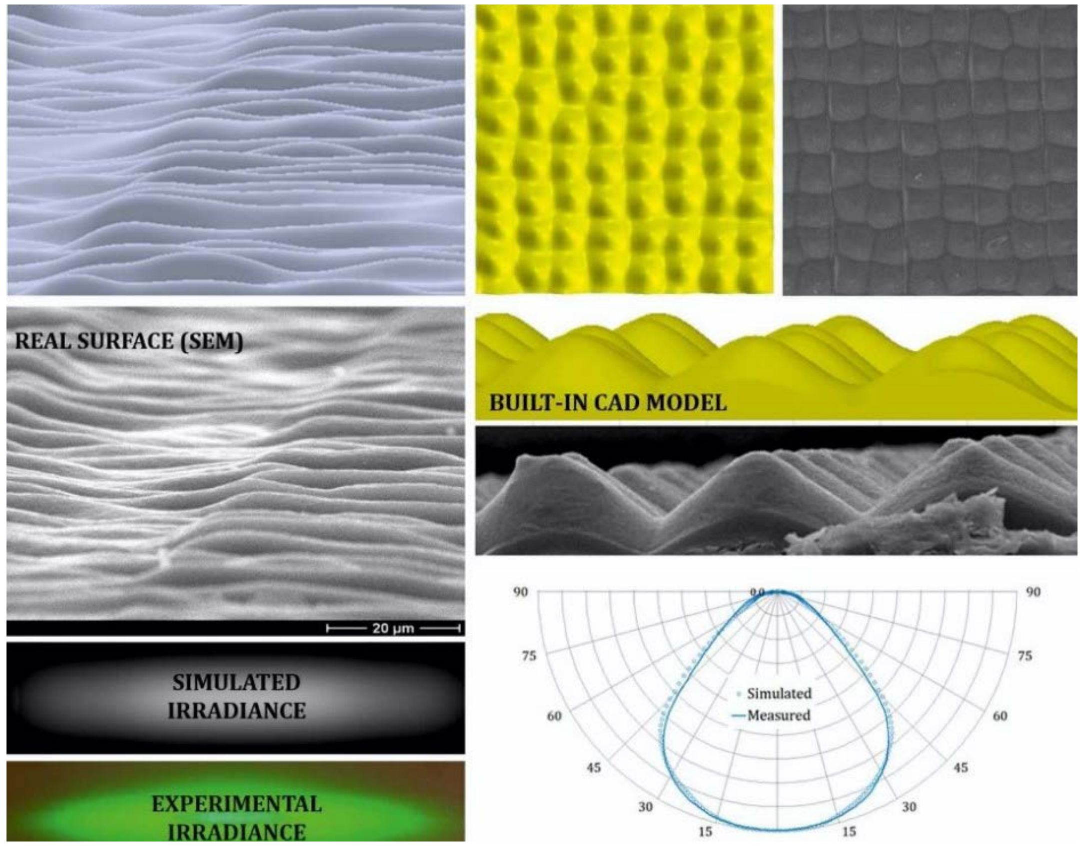


Figure 16: "Semi-empirical characterization method". CAD models and SEM picture and predicted versus observed performance (left) of a BrightView E1060 asymmetric diffuser. BrightView G-CG90 de-glaring foil (right). Predicted and measured luminous intensity of a de-glared OLED (bottom right).

State-of-the-art Technologies

Surface quality – Surface quality (low roughness) is known to downgrade the performance of all optical components, including FMLAs. Surface roughness can be measured with the available surface profilometers. However, the associated impact on performance cannot be easily predicted. Ray-tracing, the most efficient and widely used predicting approach cannot deal with surface roughness due to the short lengths of the involved features (≤100 nm). Efficient routes need to be developed to incorporate surface roughness into the PHABULOuS quality control process.

Other important properties will be measured and reported including material optical properties, stability and large-area uniformity using PHABULOuS wide range of **characterization methods**. Where necessary, existing state-of-the-art methods will be optimised and upgraded **beyond-state-of the-art** to improve their capability for the evaluation of FMLAs.

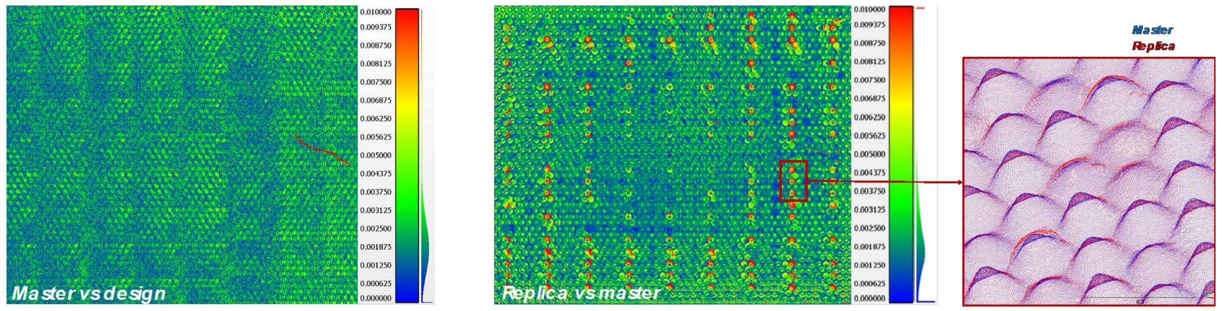


Figure 17: Surface analysis: Left) The surface roughness of the Master is compared to the Design and is virtually identical to it. Right) the Replica is compared to the Master. The replica shows relatively good form accuracy, however localized large deviations observed. Software packages used, SolidWorks, Rhinoceros, ReSurf, CloudCompare and Leica-Cyclone.

8 - Product Integration

PHABULOμS delivers product integration processes in which photonic and electronic devices/components can be assembled on substrates. Currently assembly of devices is performed using high accuracy pick-and-place machines providing alignment accuracy of +/-7 μm (3σ value) operating in both S2S and R2R mode on 200 mm wide sheet/web. Minimum device size is 100×100 μm^2. Assembly of SMD components can be performed using high speed and accuracy R2R assembly line operating up to 300 mm wide web. Line total length is 18m and it can be operated also in S2S mode. Maximum component pick-and-placement speed using Fuji NXT III Dyna Head system is 27'000 CPH. Minimum component size is 0402 (1×0.5 mm^2). Optical structure layer can be integrated on top of lighting layer using passive or active alignment methods. Typically, passive alignment methods provide up to 5-10 μm and active alignment methods down to 1 μm accuracy between layers. Integration of functional layers can be performed using lamination, UV-welding and adhesive bonding.

Both S2S and R2R assembly and integration processes will be evaluated and developed towards specific use case applications requirements during the course of project. A new 2-arm 6-axis alignment and adhesive bonding equipment providing 20 nm linear resolution and 0.005° angular resolution will be evaluated and applied in integration processes within PHABULOuS project.

MICRO-OPTICS IS...
Phabulous

State-of-the-art Technologies

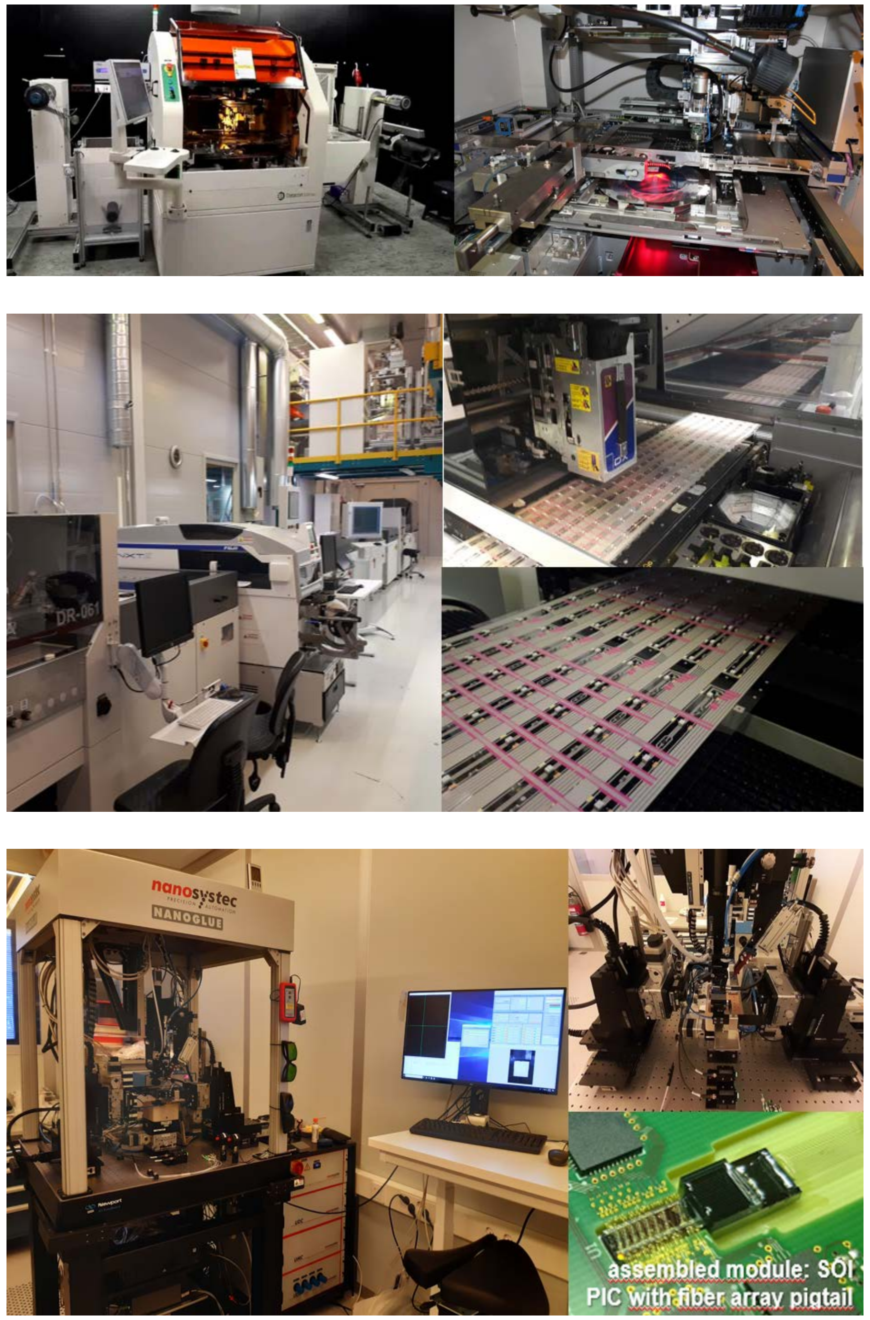


Figure 18: S2S and R2R assembly machine examples

Top) S2S/R2R device assembly machine Datacon 2200EVO.

Centre) High speed S2S/R2R SMD assembly line and Fuji NXT III pick-and-place machine.

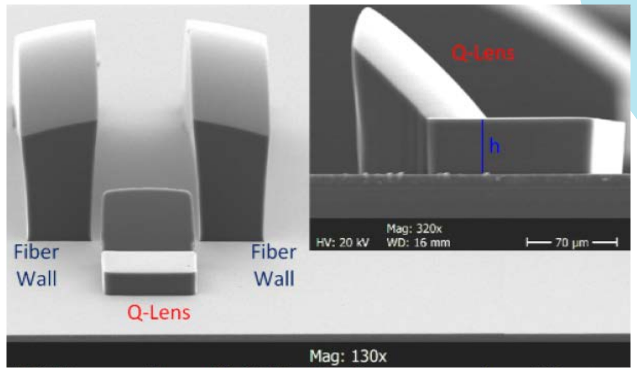
Bottom) New 2-arm 6-axis S2S alignment & assembly machine.

Market Applications

Various market applications for free-form micro-optics

Micro-lens arrays for lighting

Micro-displays for AR / VR / MR



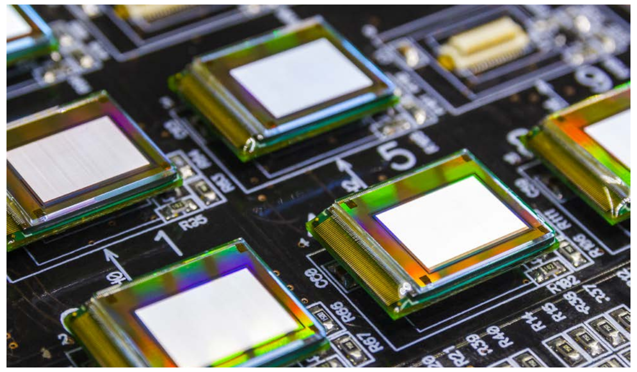
Free-form optics for photonic integrated circuits PICs

Funded by
PHOTONICS21
PHOTONICS PUBLIC PRIVATE PARTNERSHIP

MICRO-OPTICS IS...
Phabulous

Market Applications

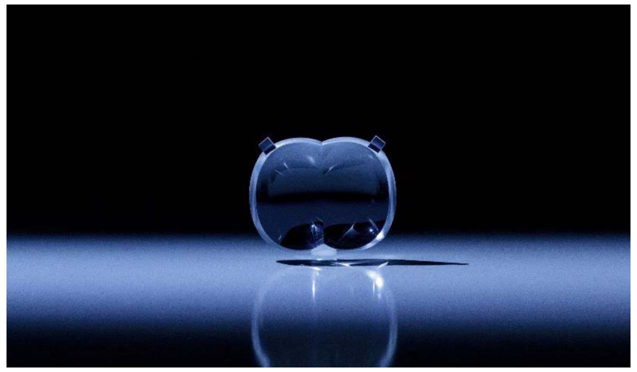
Automotive lighting



Micro-displays

Solid-state lighting

Luxury



Virtual reality

Transportation interior lighting

Funded by
PHOTONICS21
PHOTONICS PUBLIC PRIVATE PARTNERSHIP

Market Applications

Solar, Energy & Daylight

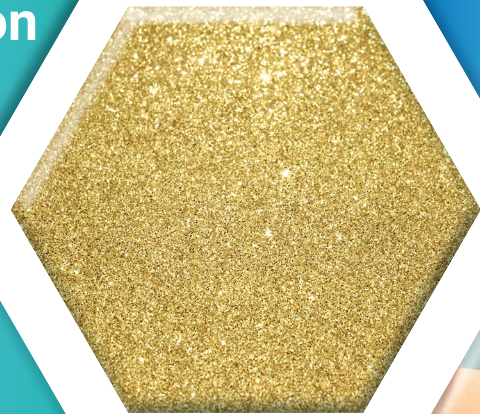
Solid state lighting

Automotive lighting

AR / VR

Market Applications

Optical communication



Health care & Life sciences

Security & Branding

Decoration & Luxury

Consumer electronics

Advanced FMLAs for VR, AR & MR

LIMBAK started in PHABULOuS as an European SME developing and licensing extreme-performance optics in the field of Virtual Reality (VR), some of these branded ThinEyes and comprising radically free-form MLAs.

Conventional rotationally-symmetric optics

Free-form multi-channel light folding optics

Figure 20: State of the art optics in commercial headsets are based on rotationally symmetric lenses (left). New headsets in 2020 are starting to be advanced optical trains, like the free-form multi-channel light-folding CLOVER lens (right), by LIMBAK

That is the case of TRENZA, one of the most advanced ThinEyes concepts. The technology can lead to video-see-through MR headsets with the size of sunglasses and superior Field of View (FOV) and angular resolution.

TRENZA is a super-thin (8-10 mm only) optical technology based on a set of free-form micro-lens arrays (MLAs) stacked between a display and user eyes designed to produce an image of the former onto the latter with the features needed in an immersive experience. Within the PHABULOuS project, LIMBAK has designed one of these variations, observing the pilot lines manufacturing constraints expected after acceleration of manufacturing services.

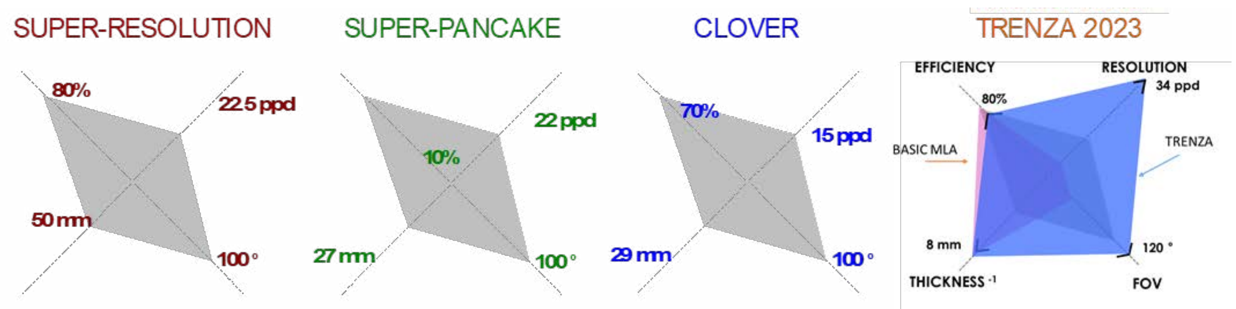


Figure 21: TRENZA 2023 as aimed to developed within PHABULOuS, benchmarked against the state of the art

Funded by

MICRO-OPTICS IS...

Market Applications

PHABULOuS has showed its capability in manufacturing complex structures as where needed for the unique features of TRENZA and is looking forward to other customers in the AR/VR domain to come forward with their specific needs and specifications.

Design - The MLAs of this design include 4 arrays of free-form lenses working in parallel, through ~ 300 optical channels. TRENZA requires the advanced optical manufacturing technologies available within PHABULOuS Pilot Line.

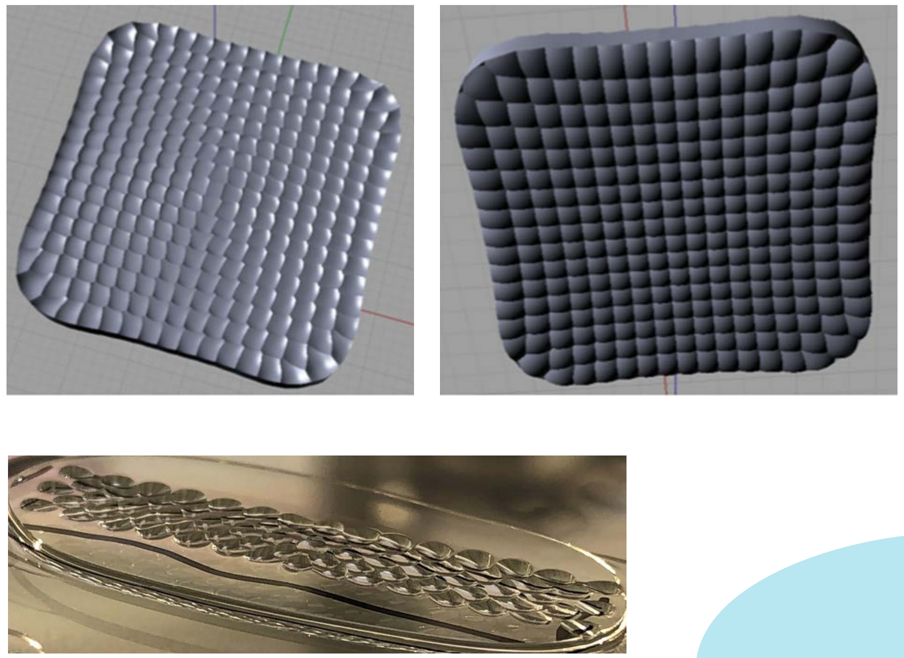


Figure 22:

Top: TRENZA 2-side MLA optical stage designed within PHABULOuS Pilot Line

Bottom: Master created within PHABULOuS Pilot Line

Funded by

Market Applications

Advanced FMLAs for OLED micro-displays

MICROOLED provides cutting-edge near-eye AMOLED displays and modules for a wide range of products, including high brightness ultra-low-power microdisplays for light AR eyewear products. In addition, under its ActiveLook® brand, the company is providing s a groundbreaking light AR eyewear solution that brings a truly heads-up, hands-free experience to industry, sports, medicine and more.

microoled
ActiveLook®

Free-form microlens arrays (FMLAs) provide great advantages for improving pixel luminance of OLED micro-displays, especially for Augmented Reality (AR) applications with see-through glasses.

Design - Main goal for MICROOLED was to control the angular shape of light output and to enhance brightness of the OLED micro-display components, especially in connection with compact, free-space optics based micro-projection systems for wearable Augmented Reality applications.

Origination - The design is characterized by a small pitch in the order of 5µm together with a high aspect ratio. PHABULOuS provided the possibility to study different methods for mastering. Finally, origination is now done both by using silicon etch technologies (CEA-Leti) as well as by laser grayscale lithography (Nanocomp), where the latter provides highest aspect ratio.

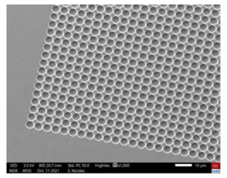


Figure 23: FMLA master by Si-etching

Market Applications

Replication - Replication is done on 200mm glass wafer by SUSS MicroOptics using a suitable polymer material. Final assembly to the microdisplay chips is then performed by CEA-Leti.

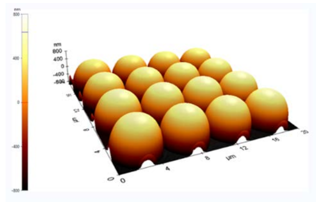


Figure 24: Replicate of FMLA master

MICROOLED will evaluate performance and manufacturability of different designs of micro-optical elements in order to choose the right manufacturing process for industrialisation of the technology.

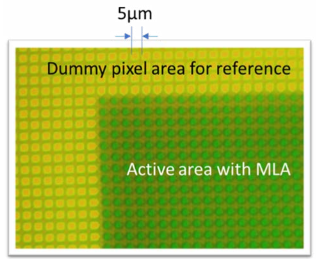


Figure 25: Assembly of FMLA replicate on microdisplay pixel matrix.

"PHABULOuS provides for us an excellent opportunity to realize and test small pitch/ high aspect ratio microlens arrays to enhance performance of our low power light AR solutions and to evaluate different solutions for future industrialization."

Gunther Haas, CTO & co-founder MICROOLED

Market Applications

Advanced FMLAs for large area direct-lit LED luminaires

SEISENBACHER is a global provider of interior solutions for the railway industry. As one of the use case partners in PHABULOuS, they are working on their next generation of luminaires with integrated free-form micro-optics for rail vehicles, buses and other means of transport.

Free-form microlens arrays (FMLAs) have the ability to produce square/rectangular illuminance patterns upon LED illumination. The individual illuminance patterns produced by each LED on an array can hence be overlapped with 100% fill factor thus rendering a uniform luminance over the luminaire outermost surface (exit aperture).

Design - SEISENBACHER joined PHABULOuS looking to develop ultrathin luminaires (thickness <10 mm) or luminaires with a significantly reduced number of LEDs (less than half for linear lighting) and a customized shape of illumination pattern due to free-form micro-optical films. The image shows the design of the free-form structure used per light source, realizing a very homogeneous irradiance on the diffuser plane.

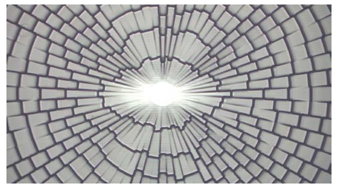


Figure 26: Design used per light source.

Origination - Besides the FMLA design, the pilot-line partner Joanneum Research further supports SEISENBACHER with the manufacturing of the FMLA master (image). The quality of the master is key for the optical appearance and has therefore to be produced with a high accuracy ensuring an outstanding surface quality. The inspection of the existing masters showed a perfect match with the light technical simulations done in the design phase.

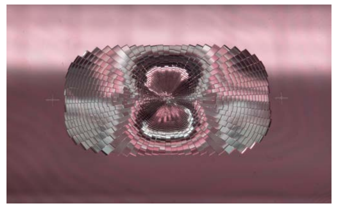


Figure 27: FMLA master

Tooling / Upscaling - In the next process step, the master is upscaled by Joanneum Research into a so-called multi-lens-array. CSEM, a further pilot-line partner, is then responsible for providing the final tool for replication, which is the galvanized multi-lens-array (image). Every single step in the process chain is of course accurately monitored to guarantee a high-quality FMLA output.

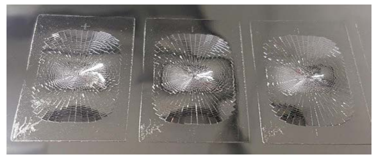


Figure 28: Galvanized multi-lens array

MICRO-OPTICS IS...
Phabulous

Market Applications

SEISENBACHER

Replication - The replicas of the optical structure are only as good as the master and the tool produced during the upscaling process. The pilot-line partner of SEISENBACHER for the replication, Morphotonics, are producing those replicas using their UV-imprint R2P (roll-to-plate) technology.

The image shows the replica (FMLAs imprinted onto a substrate), which will then be further processed and prepared for the integration into the final product.

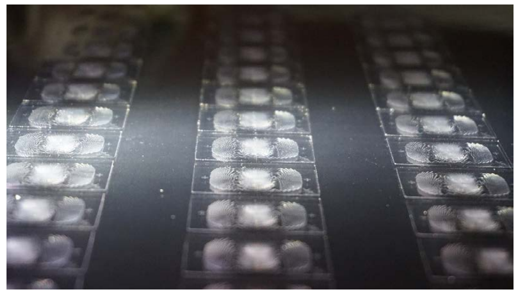


Figure 29: Replica of FMLAs imprinted onto a substrate

Integration - The image shows the final micro-optics in comparison with a ten Euro-Cent coin. The integration into the SEISENBACHER luminaires has been finished and a comprehensive type test campaign is ongoing to prove the compliance of the final product with the harsh environmental conditions on railway rolling stock applications.

The SEISENBACHER goal to miniaturize optical systems for interior lighting applications with the use of free-from micro-optics is on the right track.

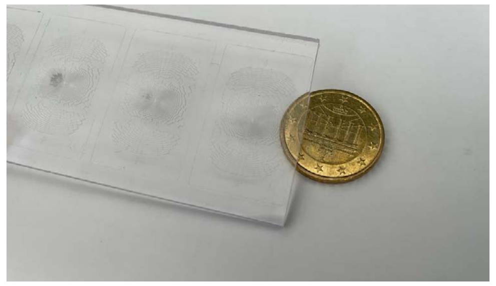


Figure 30: Final micro-optics in comparison to a 10 Euro-cent coin

"The PHABULOuS project is setting the further development of free-form micro-optics on an all-new path. SEISENBACHER is on board as one of the use-case partners, and our idea to develop a new generation of direct-lit LED luminaires with uniform luminance appearance is on a very promising way."

Christian Forstner, Head of R&D at SEISENBACHER

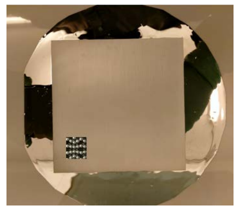
Advanced FMLAs for lighting solutions

Zumtobel Lighting GmbH is an internationally leading supplier of integral lighting solutions for professional indoor building lighting applications, targeting the fields of premium lighting solutions including, luminaires, emergency, controls and Digital Services for various building lighting application areas. As a use case of PHABULOuS they are looking to develop luminaires with asymmetric uniform light distribution.

Free-form micro-lens arrays (FMLAs) are more cost-effective, thinner and lighter than reflectors and have demonstrated potential to efficiently produce asymmetric light distributions and uniform illuminance patterns. With over 70 years of profound experience in developing optics for general lighting application Zumtobel is able to specify optical elements which meet ergonomic, human and regulatory requirements.

Design - The design was realized by Zumtobel. To achieved a high asymmetric distribution which has to be in addition very homogeneous, as the eye is very sensitive to inhomogeneity, a continuous shape was chosen. This shape incorporated steep angles, which is one of the major challenges for the technology as a whole.

Origination - For the origination different technologies have been benchmarked. The Pilot-Line partners Joanneum Research, PowerPhotonic, Wielandts UPMT and LASEA made sample coupon of the design in different scales. Very good surface quality and shape matching the design could be achieved. For the final step master of the size up 100mm in diameter have been manufactured. Alternative to manufacture a large master also the Step & Repeat (S&R) process of Joanneum Research have been implemented.



Replication - The partner Morphotonics and SUSS MicroOptics made replica on plate. For the high structure heights shrinkage is very likely to happen, but imprints of very good shape precision have been produced. Joanneum Research and Nanocomp made imprints in Roll-2-Roll (R2R) technology for lower structure heights also those were of good quality.

Quality control - After each manufacturing step quality control is important. With several partner of the Pilot Line, Fraunhofer FEP, Wielandts UPMT, SUSS MicroOptics, PowerPhotonic and Morphotonics, measurement could be linked to the simulation results and so the optical performance of the analysed.

"The collaboration with PHABULOuS generated a lot of know-how, using these technologies, to create optics for general lighting applications. The increase of the capabilities of the Pilot-Line is impressive."

Katharina Keller, Director Optics at Zumtobel

Advanced FMLAs for next generation headlights

HELLA GmbH & Co. KGaA, now operating under the overarching umbrella brand FORVIA, is one of the larger automotive suppliers worldwide and one of the use case partners in the PHABULOuS project. PHABULOuS and FORVIA HELLA are combining strength and knowledge in their field to develop the next generation headlights that incorporate free-form micro-optics.

Free-form micro-optics (FFMOs) are aesthetically appealing and provide high potential for reducing installation space, reducing weight and enable low-cost manufacturing. Several optics designs have been tested and showcased in demonstrator setups. The latest one shows the impressive improvements that have been made and highlights the low thickness of a FFMO-based approach.

Design - The idea of the FORVIA HELLA design concept is the generation of a double-sided FFMO, using a structure for pre-forming the light on the light entrance side and a free-form structure for forming the light distribution on the light output side. For latter, different structures have been tested, e.g., micro-facets, Fresnel-like structures, or completely free-form shapes. The image shows the latest design of a double-sided FFMO for a low beam application.

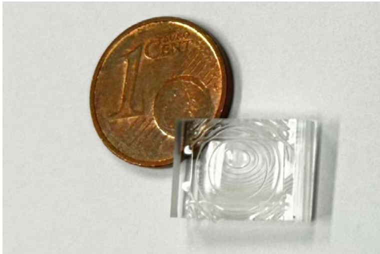


Figure 31: latest design of a double-sided FFMO realizing a low beam distribution.

Origination - Origination – The pilot-line partners that supported FORVIA HELLA with the manufacturing process are Wielandts UPMT and PowerPhotonic. Using their ultra-precision machining technique, Wielandts UPMT generated first masters of micro-Fresnel- lenses for the light entrance surface, with heigh accuracy and an impressive surface quality. The free-form structures for the output side were mastered by PowerPhotonic. In several feedback loops, HELLA and PowerPhotonic adapted the structures to the manufacturing parameters of PowerPhotonic's laser material processing technology, and the resulting masters matched the simulations perfectly.

FORVIA
HELLA

Replication - FORVIA HELLA was supported for the replication by the partners Focuslight Switzerland and Nanocomp. They showed within the replication trials, that they are to both replicate the master structures and to accurately combine the two functional surfaces of the entry and exit side in one component. The latest double-sided FFMOs were realized by Focuslight and used in a final demonstrator setup, shown in the image on the right.

Figure 32: The final demonstrator with a vertical modular design, realized by FORVIA HELLA with the optics shown in figure 31.

With regard to FORVIA HELLA's goals of using the advantages of free-form micro-optics to miniaturize optical systems for headlamp applications, the developments supported by the PHABULOµS pilot line showed great improvements over the course of the project. Due to the promising results, FORVIA HELLA is continuing to drive developments with FFMOs beyond the PHABULOuS project.

"We started with a research-level concept and demonstrated the potential of free-form micro-optics for automotive headlights in an application-oriented setup. PHABULOuS offers enormous added value for the rapid development and production of FFMOs by bundling knowledge and experience."

Dr. Daniela Karthaus, Optical Engineer at FORVIA HELLA

Advanced FMLAs for luxury foils

D. Swarovski KG defines its business by the mastery of crystal cutting and passion for innovation and design. As one of the use cases in the PHABULOuS project, Swarovski is looking for ways to bring brilliance to a larger scale using free-form micro-optics to create large sparkling surface foils and panels with high brilliance.

Free-form surface micro-structuring can provide high brilliance for foils and panels, expanding design freedom and opening the door to new designs. The high quality and cost-effective large-area roll-to-roll (R2R) and roll-to-plate (R2P) replication technologies offered by PHABULOuS are very interesting for such applications.

Design - The design for the free-form micro-optics structure in this use case was developed by Swarovski and is based on the faceted-structure of cut crystals. Different regular and irregular one- and double-sided structures were created and evaluated - always aiming for the highest sparkle.

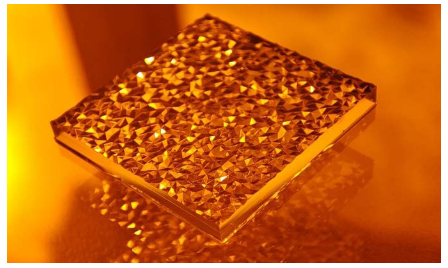


Figure 33: Faceted structure developed by Swarovski.

Origination - Two different technologies were tested for Mastering: Laser ablation and ultra-precision diamond ruling. Partners involved were Joanneum Research, PowerPhotonic and Wielandts UPMT. While laser-based methods require up-scaling by stitching, diamond ruling is directly done on a drum and thereby creates a completely seamless master. Based on tests in the internal Swarovski Light Engineering Lab and visual appearance two structures were selected due to their high-sparkle and diamond-like appearance:

- One-sided irregular structure produced via laser ablation (PowerPhotonic)
- Double-sided irregular structure created via diamond ruling (Wielandts UPMT)

Replication - Roll-2-roll replication was done by Joanneum Research and Nanocomp. Furthermore Master 2 was successfully replicated roll-2-plate on a glass substrate by Morphotonics. Silver mirror on the back of the structure was applied roll-2-roll by Fraunhofer FEP.

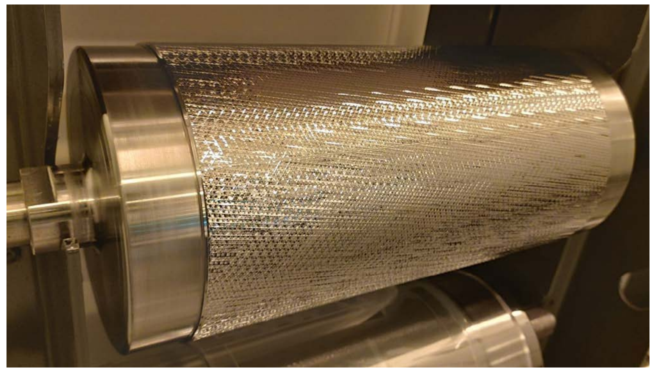


Figure 34: Roll-2-Roll replication of crystalline structure.

SWAROVSKI

Demonstrators – Various kinds of sparkling demonstrators were created within this use-case, e.g.:

- Direct imprint of one-sided structure on glass, no mirror
- Light boxes with one- and double-sided structure on PET carrier foil, no mirror
- PET carrier foil with one- and double-sided structure and mirror on one side
- PET carrier foil with one- and double-sided structure with mirror and additional print

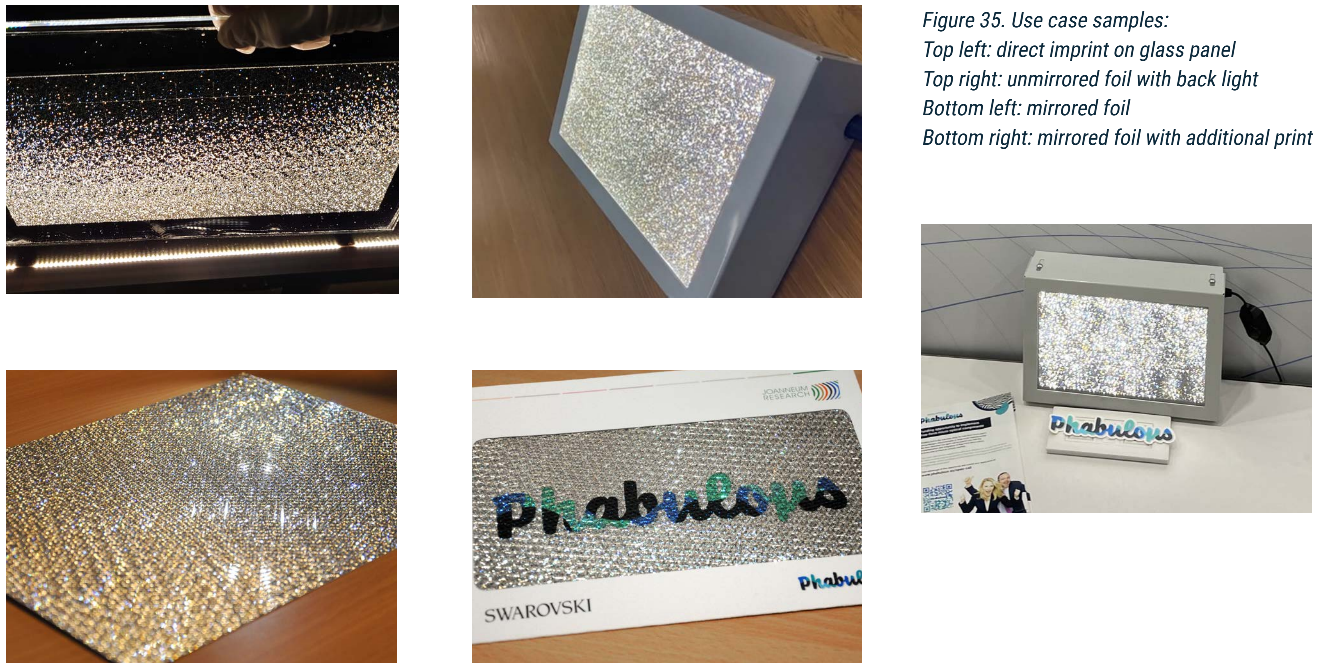
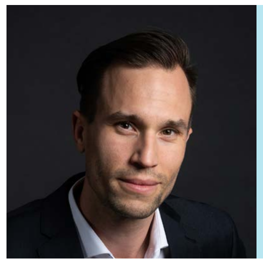


Figure 35. Use case samples:
Top left: direct imprint on glass panel
Top right: unmirrored foil with back light
Bottom left: mirrored foil
Bottom right: mirrored foil with additional print



"Our project partners within PHABULOuS did a great job in imitating the sparkle and structure of real crystals using free-form micro-optics. This technology offers an enormous potential to embellish large surfaces and will amaze customers around the globe."

Philipp Hangartner, Platform Management Components at D. Swarovski KG

Market Applications

Advanced Free-Form Optics for EProgressive Eyewear

Morrow is a deep-tech company specializing in smart eyewear, with a focus on developing eProgressive eProgressive glasses that mimic the eye's natural ability to shift focus. Their breakthrough eProgressive lenses use liquid crystal technology, enabling users to switch between near and far vision at the touch of a button. Unlike traditional multifocal glasses, Morrow's EProgressive glasses feature a dynamic electronic lens in the reading area that adjusts focus as needed, reducing the abrupt change between prescriptions. This results in a wider field of view and significantly improved visual comfort.

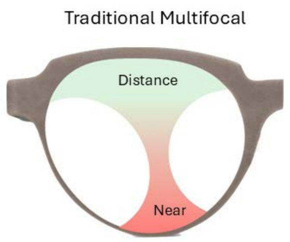


Image 36: Comparison with existing multifocalglasses.

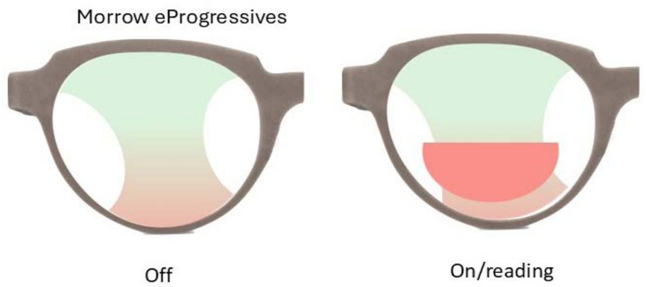


Image 37: By adding a electro-tunable lens in the far distance zone, the power difference between far and near vision can be reduced, thereby expanding the FOV and improving the visual comfort.

At the heart of Morrow's technology is a thin, flexible lens made with liquid crystals, built into a standard eyeglass lens using nanoimprinting as a critical process step. In this project Morrow aimed to scale up this production method—moving from wafer-scale wafer production to a more cost-effective roll-to-plate manufacturing.

Design - Morrow's core technology is a foil based electro-tunable liquid crystal lens, embeddable in a conventional ophthalmic lens. The foil is a multi-layered structure, containing a nanoimprinted Fresnel type lens with a liquid crystal residing on top of this lens. In the off-state the refractive index of the liquid crystal is matched with the Fresnel lens' refractive index, effectively making it optically invisible. When a voltage is applied, the refractive of the liquid crystal changes and the designed optical power of the Fresnel lens becomes active (image 3).

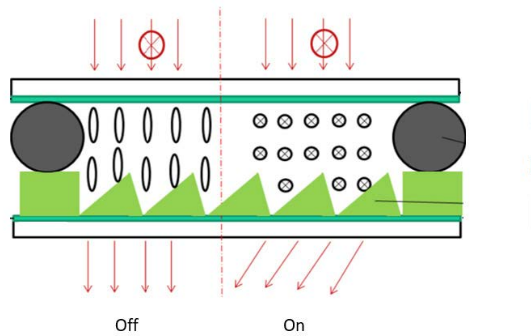


Image 38: Working principle of the electro-tunable lens. In the off-state the liquid crystal is index matched with the Fresnel lens, rendering it invisible. In the On-state, the index difference leads to the Fresnel lens being optically active.

Market Applications

MORROW

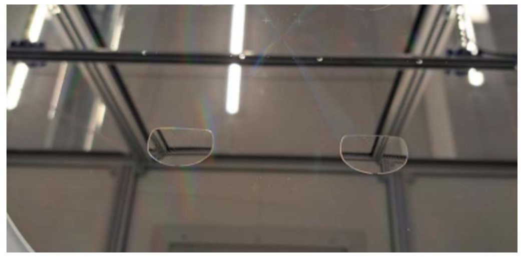


Image 39: Master

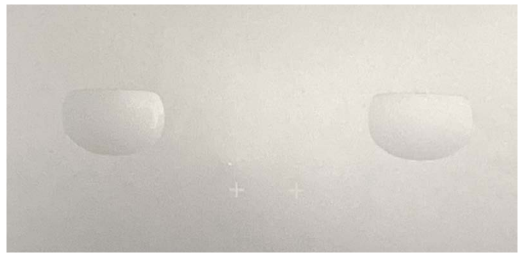


Image 40: Imprinted Fresnel structure.

Image 41: Morrow's Autofocal glasses

Origination - Wielandts UPMT made the monolithic masters using their patended single point diamond turning services with NiP plating on an aluminum master. Alignment marks and spacers where added using their diamond milling capabilties. Morphotonics supported with the process and material development of Roll-to-Plate nanoimprint including anti-sticking treatment of master and flex stamp fabrication.

Replication - CSEM imprinted the structures on a glass substrate on their roll-2-plate equipment from Morphotonics. An ITO coated foil was laminated onto the glass substrates and pretreated with an atmospheric plasma for improved adhesion of the imprint. The flexible stamp received an anti-static treatment after demolding.

Post-processing - LASEA has used their femtosecond laser machines to perform the laser processing for the ITO isolation/ablation and added markings to the imprints. They successfully used their laser cutting capabilities to cut the stacked foil in the right shape for both the left and right sided lens without discoloration and delamination effects and without any residual from ablation on the substrate.

"The PHABULOuS project successfully demonstrated a crucial step for us: scaling our lens production from wafer-scale to roll-2-plate replication. This proves we can achieve scalable and cost-effective manufacturing, which is a significant win for the commercial potential of our eProgressive lens technology".

Anshul Sharma, Head of Operations at Morrow

Driving Innovation in Miniaturized IR Illumination

4K-MEMS specializes in the development of cutting-edge broadband infrared emitters for embedded sensing applications. Their patented technology utilizes advanced microfabrication techniques to create compact, efficient light sources, enabling integration into consumer products.

Free-form micro-optics has the capability to ensure precise light collection and direction in a compact design, emphasizing efficiency and transformative potential in embedded sensing systems. 4K-MEMS aims to source a custom microlens array designed for their next generation of IR gas sensors.

Design - To meet the optical performance and miniaturization demands of consumer electronics, 4K-MEMS has developed an innovative microlens array tailored to its broadband IR emitters. The project considered more conventional circular lenses as well as square-shaped free-form lenses. These geometries were selected to compare optical performance and manufacturability, as well as to assess how shape influences light collection and beam shaping. The design process included detailed optical simulations and CAD modelling to ensure compatibility with wafer-level manufacturing techniques.

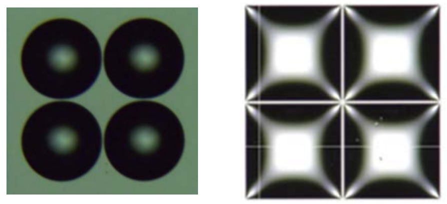


Image 42: The two different designs: one with round lenses (left) and a second with square shaped free form lenses (right).

Origination and Replication - The designs were realized on a silicon wafer developed by Focuslight Switzerland. High-precision origination techniques ensured exceptional form accuracy and surface quality. A patterned spectral filter coating applied to the circular lenses, introducing a functional distinction and enabling comparative analysis. CSEM performed beam profile, divergence, and spectral response measurements at 3.9 and 4.2 microns, both for coated and uncoated lenses. The lenses were then scaled to wafer-level to demonstrate reproducibility and performance consistency.

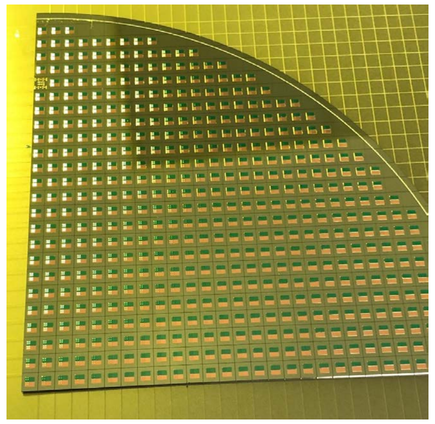


Image 43: Quarter wafer with the filters on the lenses after dicing.

Key Advantages:

- High-quality prototyping with free-form surface capabilities
- Scalable manufacturing with consistent optical performance
- Thin-film coatings for enhanced functionality and durability

Integration - In the final phase, the microlens arrays were bonded to IR emitter chips by CSEM. This assembly process required precise alignment to ensure optimal optical coupling between the lenses and the emitters. Initial efforts focused on assessing mechanical and optical requirements, selecting appropriate adhesives, and developing proof-of-concept assemblies. Once validated, the lens arrays were mounted onto packaged emitters in a controlled process that preserved alignment and optical integrity.

MICRO-OPTICS IS...
Phabulous

Market Applications

4K-MEMS

Characterization - CSEM carried out a comprehensive performance evaluation to assess both the optical quality of the lenses and their integration with the NIR emitters. The characterization included detailed measurements of beam profiles and divergence angles, and spectral responses for both the coated and uncoated lenses. These tests confirmed that the lenses effectively shaped and collimated the emitter output into the desired beam profile. The accuracy of the system was further validated through irradiance maps, which demonstrated a strong correlation between expected and measured performance, highlighting the precision and robustness of the optical system.

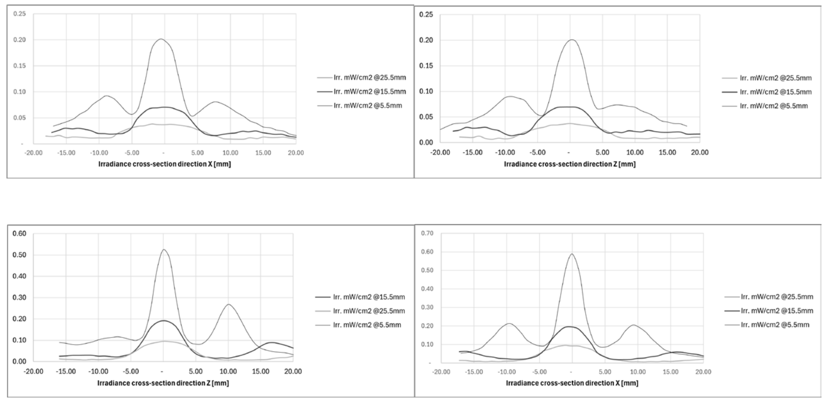


Image 44: Irradiance analysis for uncoated circular lenses (top) and uncoated square lenses (bottom)

Motivation - By leveraging freeform micro-optics, 4K-MEMS was able to develop a highly compact optical module that integrates a micro-emitter able to generate signal and reference beams in a single package. This miniaturization opens doors to integration into mobile handheld devices, addressing consumer demands for compact and efficient sensing technologies in diverse applications such as wearables, smartphones, and healthcare devices.

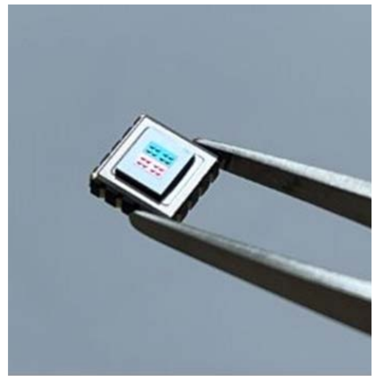


Image 45: Prototype of a CO_2 sensing module with 4 sets of 4 microlenses

"4K-MEMS is setting a new benchmark for IR emitter technologies. Through the support of PHABULOuS and strategic industry partnerships, we made great advancements towards innovative, high-performance IR sensing solutions."

Ross Stanley, Chief Scientific Officer at 4K-MEMS

Market Applications

Free-form imaging-grade components for various applications

mcd - modern camera designs GmbH is developing and bringing to market a proprietary UV-replication technology for monolithic aspherical polymer lenses and objective lenses made thereof. Their room-temperature approach allows the same design degrees of freedom and imaging quality as injection molding but benefits from lower tooling costs. At the same time, it employs high process parallelization and material temperature stability such as wafer level optics, making it an attractive manufacturing technology also for harsher environments and/or very high-volume imaging use cases.

The goal of mcd working with PHABULOuS was the first-time-demonstration of complex lens stacks produced by mcd´s energy saving and fully scalable replication technique.

Design - mcd developed several opto-mechanical designs using refractive aspherical surfaces for high-resolution imaging optics

Mastering and Origination - For this purpose, the main service requested was diamond micro-machining of master structures which were created by Wielandts UPMT. Form errors and surfaces roughnesses of the required master structures were as little as 100nm and 3nm rms, respectively.

Replication - The replication was done by mcd through their proprietary UV-replication technology. Different kinds of demonstrator systems with varying numbers of elements, resolutions, F/#s and fields of view were manufactured and tested by mcd.

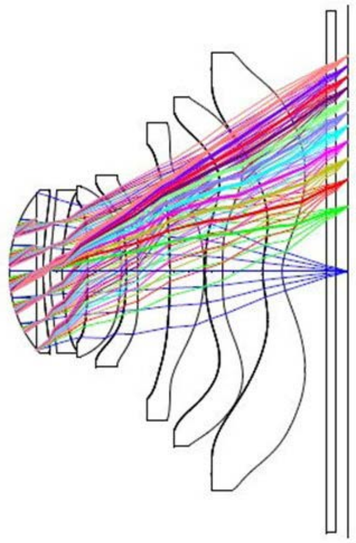


Image 46: Layout of a polymer objective lens for smartphone applications with double-digit Megapixel-resolution – challenges are short total track length requirement, small f-number and large lens size on image side.

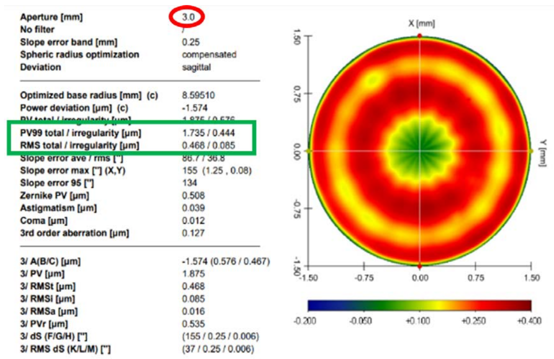


Image 47: Form error measurement on replicated lens surface shows close to diffraction limited performance for medium lens sizes.

Market Applications

mcd
modern camera designs

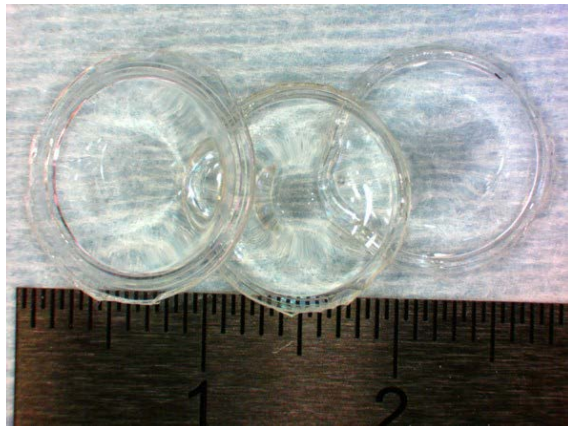


Image 48: Highly aspherical ("gull wing") monolithic polymer lens with 10mm diameter realized by mcd's UV-replication technology, masters originated by Wielandts UPMT.

Integration - The replicated optics form the necessary basis for the success of mcd's replication technology and result in high image quality, yield and manufacturing volumes. The objective lenses find applications ranging from compact digital camera modules for medical (single-use or re-usable chip-on-the-tip endoscopes) over automotive- and AR/VR cameras up to complex high-resolution smartphone camera modules.

Image 49: Test images captured with an intermediate camera demo system using a 3-element f/2-objective lens suitable for automotive applications.

"The collaboration with PHABULOuS was transparent and efficient and the executing partner Wielandts UPMT was swift, clear and reliable. The quality of the master structures was excellent and rare to find in the combination of low form error and low surface roughness. This allowed us to demonstrate our capability to produce next generation of highly complex objective lens stacks for the first time."

Jacques Duparré, Co-founder, Business development manager and Lens design lead at mcd - modern camera designs GmbH

Robust optical fiber array connector for advanced datacom

SFEZ Technologies Ltd is a photonics innovation company that provides advanced solutions and strategic guidance for complex optical and photonic projects. The company offers tailored photonics solutions and explores collaborative opportunities for joint ventures in photonics innovation. For the datacom market they have developed LightBridge™, a technology platform for high density, non-contact and scalable photonics connectability.

SFEZ contacted PHABULOuS to develop LightBridge, a low-cost, high volume and robust optical fibre array connector for advanced datacom needs to provide major benefits over standard (physical contact) connectors. Advantages of such connectors are the relaxed positioning accuracy of the individual fibres, the low sensitivity to dust and the high fiber ports density.

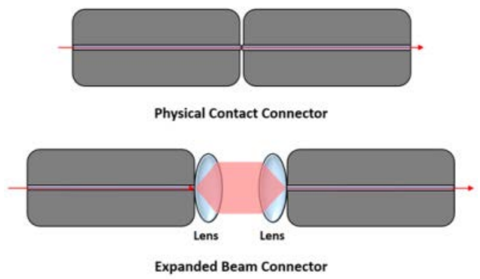


Image 50: Concept expanded beam connector (bottom) versus physical connector (top).

Design - The solution proposed by Sfez Technologies is based on two aligned arrays of polymer microlenses forming an array of achromatic and athermic doublets, using properly chosen polymer material with complementary properties (CTE, dn/dT). The proposed solution is based on arrays of polymer microlenses obtained by nanoimprint.

Origination - In order to manufacture the master, CSEM created the photomasks design, including alignment marks for wafer-to-wafer alignment and alignment pins/holes to enable bonding with the required accuracy. Two different spherical lens arrays were mastered by reflow. From these masters, a fabrication stamp (submaster) was produced with chromium apertures with an anti-reflective nano-texture in UV-curable polymeric resin on 8” wafers.

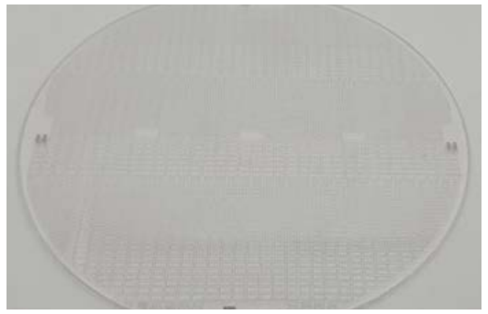


Image 51: mold layer

Replication - Replication was done by CSEM on thin glass wafers for which they created a new process enabling the use of carrier substrates. The microlens arrays (MLAs) were formed using MA8 mask aligners and wafer-scale UV nanoimprint techniques, achieving sub-micron imprinting accuracy.

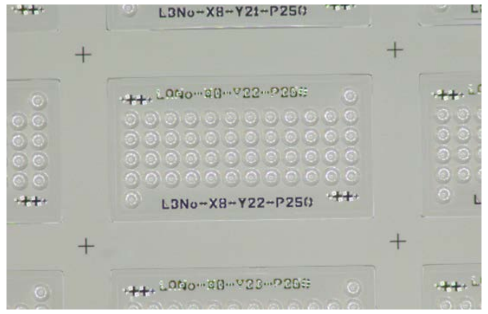


Image 52: replicated optics

Bonding - The replicated wafers were sent to VTT to be bonded in pairs, going from an expected 3 µm accuracy alignment to a desired 1,5 µm accuracy alignment. In close collaboration, CSEM and VTT worked together on wafer geometry, bonding conditions, and alignment features to achieve high precision bonding with very high (~1µm) accuracy for 6-inch glass wafers.

Test & Integration - The initial integration of the lens array with the MPO/MT ferrule has been completed, and testing is currently underway. With temperature stability ranging from -50 °C to +150 °C and excellent sealing against humidity, we believe the current version of LightBridge offers an outstanding solution for multi-fiber applications in harsh environments. To confirm this, we will conduct comprehensive environmental tests to validate the product for these demanding conditions. In parallel, we are planning to integrate the lens array with MPO/MT ferrules at the wafer level to reduce production costs and ensure compatibility with the cost structures required by data center applications.

Image 53: demonstrator

“Collaborating with PHABULOuS was highly professional, and the results were delivered quickly, successfully demonstrating new concepts in optical communication, compatible with high-volume production — a crucial step toward advancing to the next phase of scaling up the technology.”

Dr. Bruno Sfez, CEO at Sfez Technologies

Cost-effective fabrication of fiber-to-PIC interconnects

InSpek develops and provides optical sensors based on Raman spectroscopy and integrated photonics to monitor biological and chemical processes and optimize their performance. PHABULOuS provided a unique opportunity to test alternative ways of packaging their photonic integrated circuits (PICs) with optical fibers.

Coupling light in and out of PICs is known to be challenging due to the tight alignment tolerances at interfaces. Thus, an active alignment technique is typically used to connect the chips to optical fibers, which significantly increases the cost of packaging. The expertise in nanoimprint technology through PHABULOuS offered an attractive alternative to optimize the cost of packaging photonic chips.

Design - The design phase lead by CSEM included simulations of coupling losses due to geometrical misalignment, as well as creating a custom layout of passive alignment structures matching the waveguides on the photonic chips from InSpek.

Origination - The photomask-based master has been prepared by CSEM via the direct laser writing approach and included variations of passive alignment structures geometry to reach the optimal coupling efficiency.

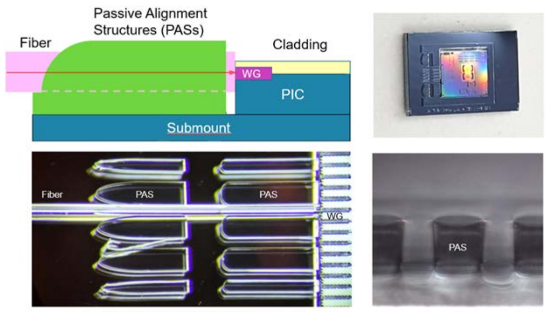


Image 54: Concept and implementation of the imprinted passive alignment structures for edge couplers.

Replication - UV-imprinting with a mask aligner was used by CSEM to replicate the passive alignment structures on sub-mounts holding the InSpek photonic chips. A special attention was given to the choice of the UV-curable resin, that should withstand autoclaving conditions for biological applications, while also giving minimal shrinkage artefacts in the UV curing process.

Integration - The final stage included interfacing the imprinted assembly and the PIC chip from InSpek with optical fibers for functional testing. This process, carried out by partner CSEM, required precise integration of the chip, fibers and fiber alignment structures ensuring passive alignment of fiber to the chip with minimal packaging insertion losses.

Demonstrators - Several demonstrators comprising PICs from InSpek and passively aligned optical fibers have been fabricated and successfully measured. The measurements included the characterization of coupling losses done by CSEM as a part of quality control and later validated by InSpek, as well as Raman signal collection from the chip done on the InSpek side. A possibility of wafer-scale imprinting of passive alignment structures has also been demonstrated, which has a potential of drastically bringing down the cost of packaging photonic chips.

inSpek
ENLIGHTENING YOUR PROCESSES

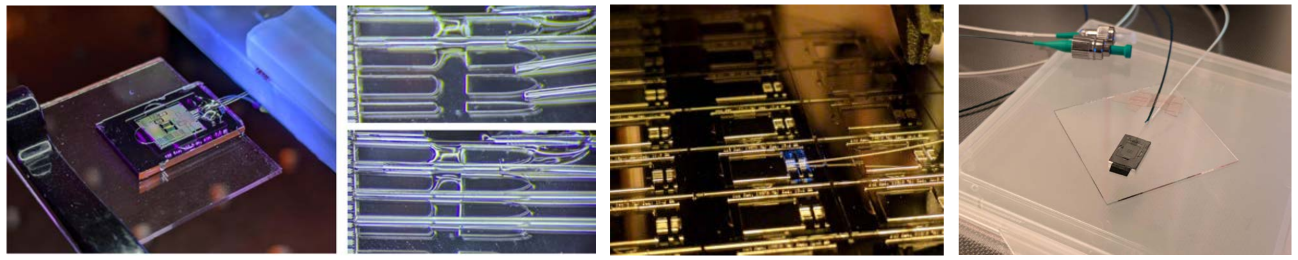


Image 55: Fiber insertion and fixing process guided by the imprinted passive alignment structures. A wafer-scale imprint and assembly can be implemented to reduce the assembly costs. A fully-assembled PIC device ready for optical testing.

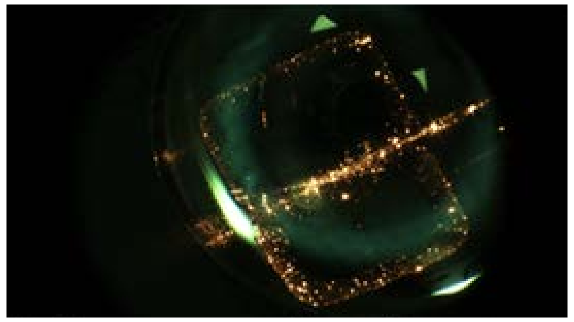


Image 56: Top view of the NIR-excited PIC Raman sensor with a droplet of analyte on top. The NIR light is propagating at the surface of the chip at the contact with the analyte.

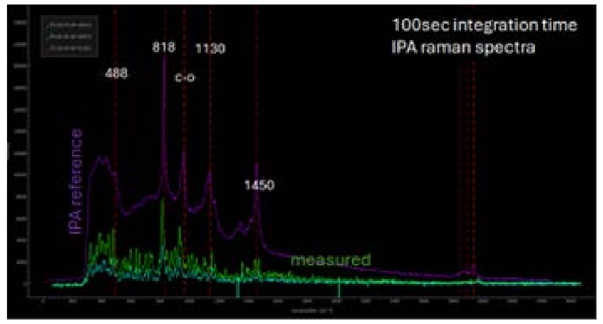


Image 57: Comparison of the collected Raman spectra on the prototype (green) with a reference of IPA (purple), the dashed red line indicate the Raman signature of IPA.

"PHABULOuS provided us a valuable opportunity to explore packaging structures that could facilitate access to passive packaging solutions. By enabling single-use biosensors and interchangeable optical probes, we aimed to enhance the flexibility and scalability of our Raman spectroscopy system. While the project encountered technical challenges, the insights gained have been instrumental in refining our approach for future developments."

Dorian Sanchez, Photonics Engineer at InSpek

Market Applications

Improved Light Coupling for Flexible Organic Photovoltaics

Dracula Technologies is specialist in printed organic photovoltaic (OPV) modules. Through their innovative LAYER® technology their modules can efficiently harvest energy from ambient light - even in low-light indoor environments - eliminating the need for traditional batteries in low-power electronic devices.

Free-form micro-optics can improve both the light collection in the active solar layers as well as serve as a protection layer for the PET surface while maintaining transparancy. By introducing an irregular optical microstructure, the angle of incoming light can be modified, extending its path through the absorber while visually masking internal solar cell features.

Design - To test the feasibility, Joanneum Research tested several designs such as domes and pyramids and carried out carried out comprehensive optical simulations and structural design work based on the refractive indices of PET and UV-curable resins. The outcome was a fully defined opto-mechanical design intended for imprinting onto PET substrates.

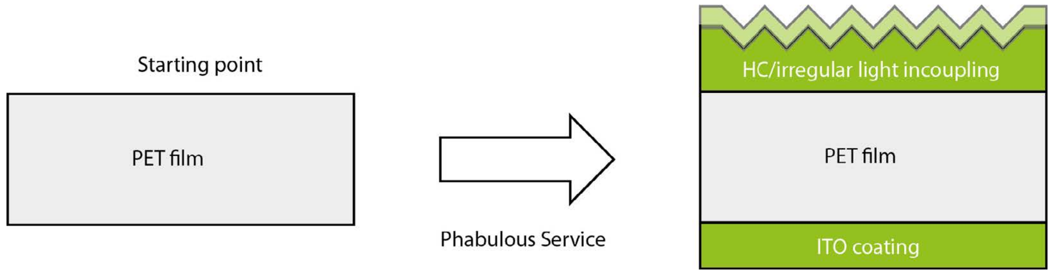


Image 58: concept for the DRACUA substrate with the improvements by PHABULOuS.

Prototyping - In parallel, Fraunhofer FEP provided rapid functional samples using an existing irregular master structure. The micro-patterned films were embossed and cured onto PET, followed by plasma-enhanced surface treatment to increase transparency. A key achievement was the successful integration of ITO sputtering on the backside, forming a complete OPV-compatible layer stack. These samples demonstrated enhanced diffuse transmission and optical efficiency compared to Dracula's standard substrate.

Origination - Joanneum Research created the high-resolution imprint master using grayscale laser lithography. This was then metallized and used for batch UV imprinting onto PET foils using custom-selected UV-curable resin. The replication achieved the desired optical fidelity and scratch-resistant properties, providing Dracula with realistic samples for performance testing and integration assessments.

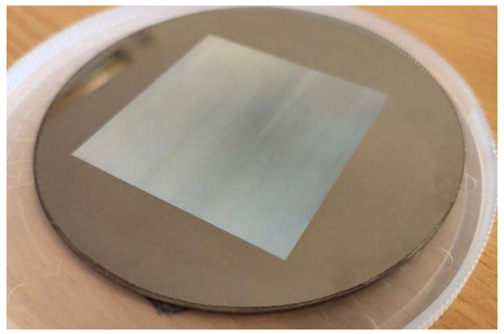


Image 59: Ni-plated master on 4 inch substrate

Funded by
PHOTONICS21
PHOTONICS PUBLIC PRIVATE PARTNERSHIP

MICRO-OPTICS IS...
Phabulous

Market Applications

DRACULA TECHNOLOGIES

Integration - Fraunhofer FEP also prepared coated samples applied directly onto solar cells, verifying feasibility for integration into the actual photovoltaic assembly without damaging the active materials. Pilot tests showed that enhanced diffuse light transmission and mechanical durability could be achieved with existing embossing technologies, and upscaling to roll-to-roll. As part of the study, also routes for antireflection coatings and ITO sputtering were explored.

By integrating microstructured optical films, Dracula Technologies has validated a path forward for self-powered, printable solar technologies that are more robust and optically efficient. These developments support Dracula's mission to deliver energy-autonomous smart devices powered by light.

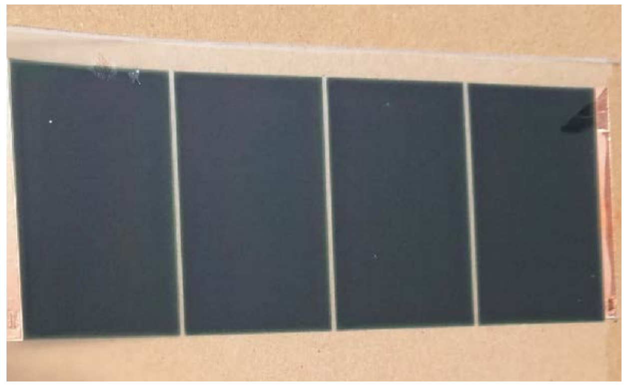


Image 60: solar cell with a hardcoat with micro-optical structures

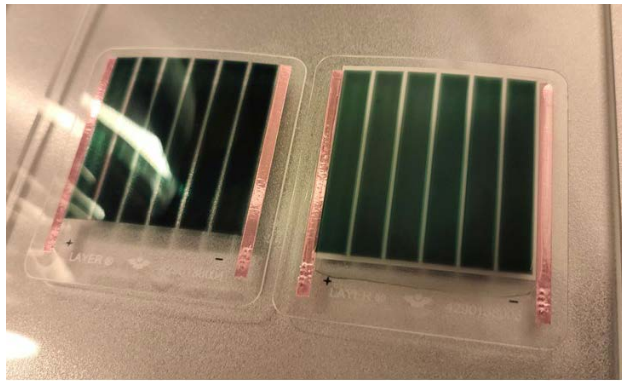


Image 61: OPV modules; one without the extra layer (left) and one with the layer that includes the imprinted micro-optical structures (right)

"The developments in this study proved the ability to increase light capture using micro-optical structures while protecting our solar films. PHABULOuS has been a great partner to verify the concept and showing us the route towards scalable solutions to improve the efficiency of our OPV panels."

Dr. Hani Kanaan, Head of Business Development at Dracula Technologies

Funded by
PHOTONICS21
PHOTONICS PUBLIC PRIVATE PARTNERSHIP

Next-Generation Retro Reflectors in Automotive

G² Industrial Engineering is an Austrian company with a focus on the development of systems for both the interior and exterior of vehicles. Another key area of expertise is automotive lighting development, providing innovative solutions to meet industry demands.

G² Industrial Engineering targeted to leverage advanced micro-optics technology for the development of an innovative retroreflector, marking a significant advancement in their optical systems.

Retroreflective Principle - The fundamental principle of retroreflection is the redirection of incoming electromagnetic waves back toward their source. This is typically achieved through precisely engineered optical geometries that optimize reflection efficiency. Various shapes and designs can be used to achieve retroreflection. The most common approach in the automotive industry involves three perpendicular reflective surfaces that meet at 90° angles to form a cube-corner configuration.

Current Status of Retroreflectors in the Automotive Industry - Retroreflectors play a crucial role in automotive lighting, enhancing vehicle visibility and safety in low-light conditions. Regulatory requirements mandate the use of retroreflectors in various regions, with North America requiring both front (orange) and rear (red) retroreflectors on vehicle lighting systems, while European regulations only require them on rear lamps. These components must meet strict performance standards, ensuring they effectively reflect incoming light back toward its source to alert other road users.

From a design perspective, achieving the legally required retroreflective performance presents notable challenges. Passenger cars typically require a minimum reflective surface of approximately 25 cm², with individual optical elements ranging from 2 to 3 mm in size. The manufacturing of the optical surfaces of retroreflectors requires a very precise process in which each individual reflective element corresponds to a single pin within the injection molding tool. Any imperfections or deviations in these surfaces can significantly affect performance.

Development of Micro-Optics Retroreflector - The primary objective was to create a highly efficient retroreflector, mostly for automotive application which was done in collaboration with PHABULOuS partner JOANNEUM RESEARCH. The functionality was achieved through the periodic arrangement of pyramid-structured reflectors with an equilateral triangle base area. Further, this design eases handling during production compared to corner-cube reflectors.

The project involved optical simulation, pattern design and origination, tooling and replication including quality control, and integration of a micro -structured surface covering an area of 1 cm², with individual microstructures reaching a maximum height of 30 µm. The focus on aesthetic quality of the micro-optics was a key factor in the study, paving the way for replacing the large optics.

A specialized algorithm for the calculation of the pyramid microstructures was designed for an area of 1 cm². The angular dependent reflection of the structures was simulated and resulted in efficient reflection for lower angles of incidence (up to theta 20 degree).

MICRO-OPTICS IS... Phabulous

Market Applications

The origination process employed maskless grayscale laser lithography (MALA) in a photosensitive resin, exposed according to the calculated location-dependent light doses (virtual photomask) on a rigid substrate. The quality of the originated surfaces was validated by high-resolution images provided by SEM (see image 62).

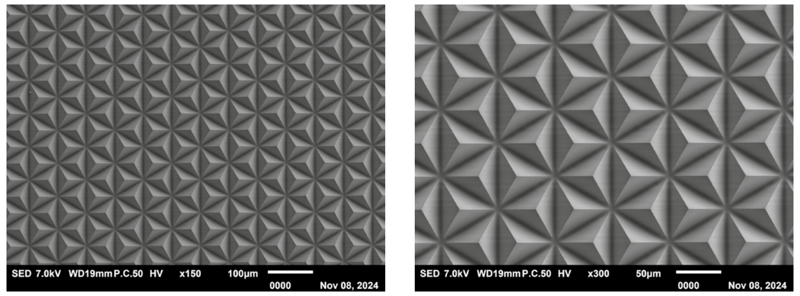


Image 62: High-resolution SEM images of the microstructures originated by MALA.

A durable Nickel master served as an inverted stamp for the replication process (see image 63). The structures were UV imprinted on flexible substrates with high precision and reproducibility.

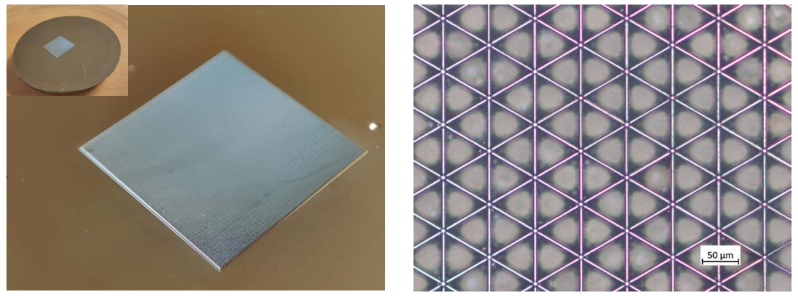


Image 63: Left: Photography of the Nickel tool, Right: microscopic close up image of the retroreflecting structures.

Conclusion - The feasibility study confirmed the anticipated optical performance of the micro-structured retroreflector through both simulation and fabrication. However, deviations in optical performance were observed, primarily due to not completely optimized process parameters. Despite this, the core retroreflective functionality was successfully validated through simulation, providing a solid foundation for further development and optimization.

"Building on these results, G² Industrial Engineering is now transitioning to industrial-scale production of micro-optical retroreflector units. Thanks to cooperation with PHABULOuS, this transition is supported by strategic partnerships with key industry suppliers, ensuring consistent optical performance and high-precision replication."

Dr. Albert Krammer, the head of the R&D department at G² Industrial Engineering

Optical modelling services for microstructured illumination plates

Microrelleus S.L. is a provider of advanced laser microstructuring and industrial engraving services, and specializes in femtosecond and nanosecond laser technologies, offering high-precision microstructuring, surface texturing, and engraving solutions for a wide range of industries and is particularly strong in the automotive lighting industry.

Image 64: The photometry done on the injected part and prototype

Microrelleus contacted PHABULOuS to evaluate the feasibility of developing a standard modelling and photometry approach. Microrelleus has reported a common mismatch between the optical simulation of a design (micro-optics distributed over a specific part) and the photometry done on the fabricated part. The latter can be directly engraved PMMA prototypes or parts injected with the engraved mold. Therefore, Microrelleus has requested PHABULOuS' support to evaluate the feasibility of developing a standard modelling and photometry approach that could later on be offered as a service to Microrelleus' customers.

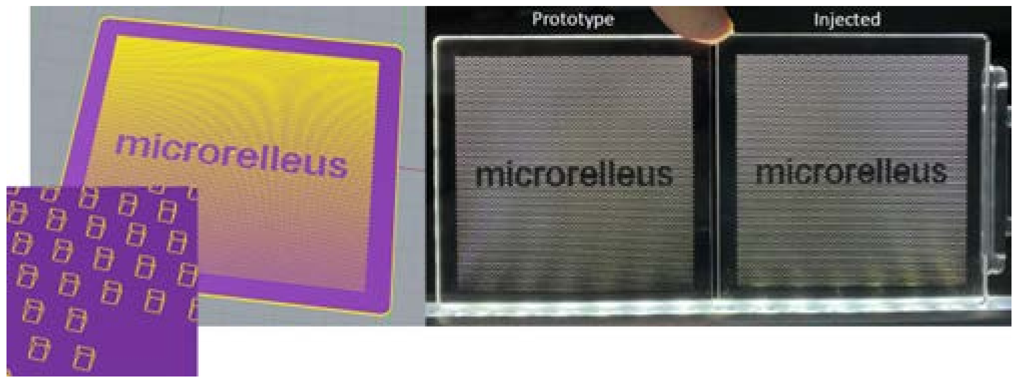


Image 65. CAD file (left), prototype (center) and injected part (right) provided by Microrelleus to CSEM.

microrelleus

Design & Simulations - Microrelleus and CSEM jointly defined the requirements of the standard model to be set up both in the illumination software (Synopsys LightTools) and experimentally. A RGBW thin LED stripe was used to illuminate the edge of a flat 70×70 mm2 part. The edge coupled light is outcoupled by the micro-optics with a pattern which is imaged with CSEM's 2D color analyzer for photometry. Microrelleus delivered two flat 70×70mm2 parts with micro-optics: the prototype and its injection-molded version (see image 65). Various camera objectives, LED powers, LED colors and measurement distances have been investigated.

Results – The experimental results show that the injection-molded part is slightly brighter than the prototype, due to higher roughness. Secondly, CSEM added roughness, in the form of Gaussian simple scattering, to the ideal CAD file delivered by Microrelleus in order to match the simulations with the measurements (image 66). These results are of high interest for Microrelleus for further investigation.

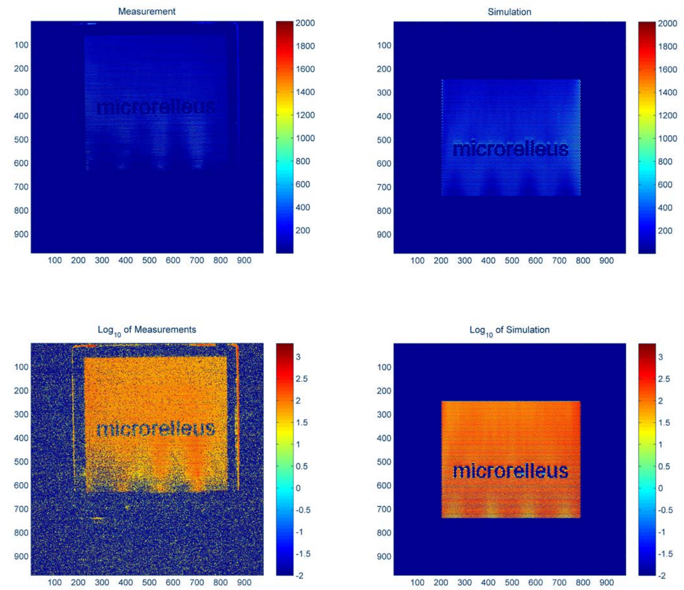


Image 66. Experimental measurement (left column) versus optical simulations (right column). Luminance maps in cd/m2 (nits) in linear scale (top row) and logarithmic scale (bottom row)

"PHABULOuS and its partners have been a great support in developing a standardized modeling and photometry approach, so companies can close the gap between simulation and reality, reduce development risks, and accelerate innovation in micro-optics-enabled products."

Raúl García, CEO at Microrelleus

Phabulous

OUR PROJECT PARTNERS

csem — FACING THE CHALLENGES OF OUR TIME
JOANNEUM RESEARCH
VTT
Fraunhofer FEP
leti cea tech
FOCUSLIGHT — Never stop exploring
MORPHOTONICS
NANOCOMP
Wielandts upmt
LASEA
PowerPhotonic
EPIC — EUROPEAN PHOTONICS INDUSTRY CONSORTIUM
AMIRES

www.phabulousproject.eu

Funded by

PHOTONICS21

PHOTONICS PUBLIC PRIVATE PARTNERSHIP

PHABULOuS is an EC funded initiative, in a public-private partnership with Photonics21. **www.photonics21.org**

PHABULOuS has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement nº 871710.