Phabulous

Pilot Line Handbook

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

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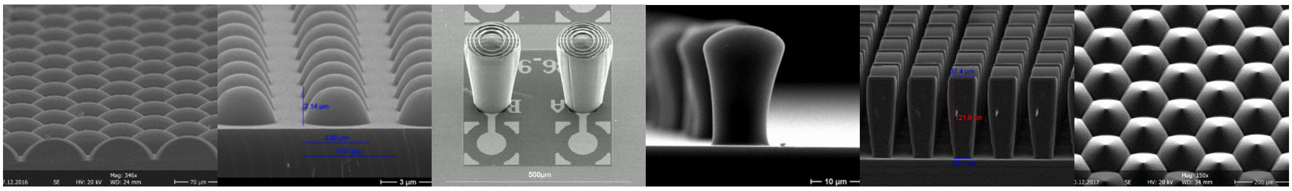
Introducing PHABULOμS

A new era for free-form micro-optics

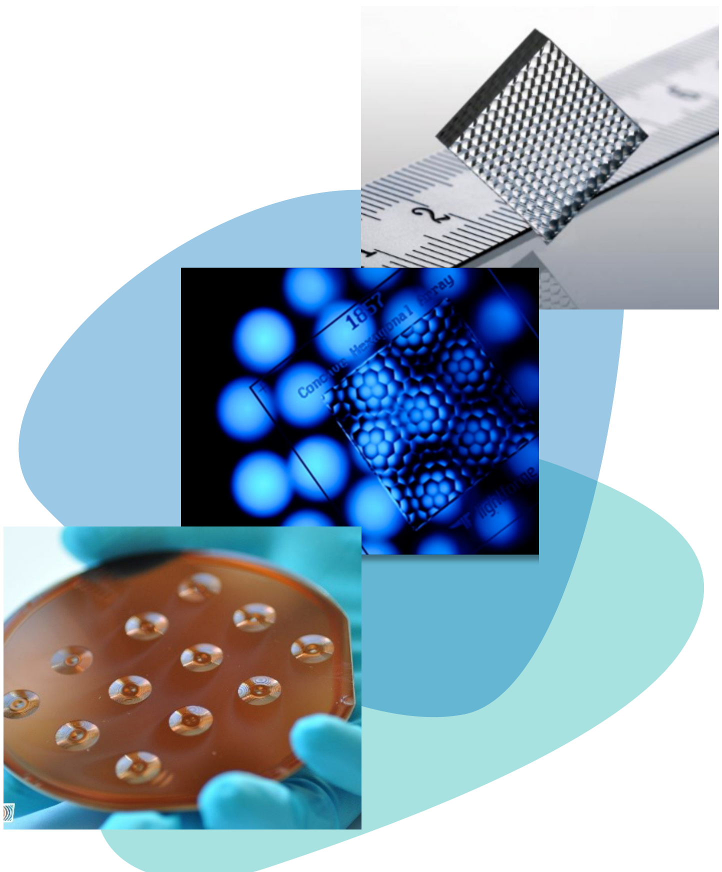
Free-form Micro-optics are micro-optical components:

- 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



Challenging technology

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

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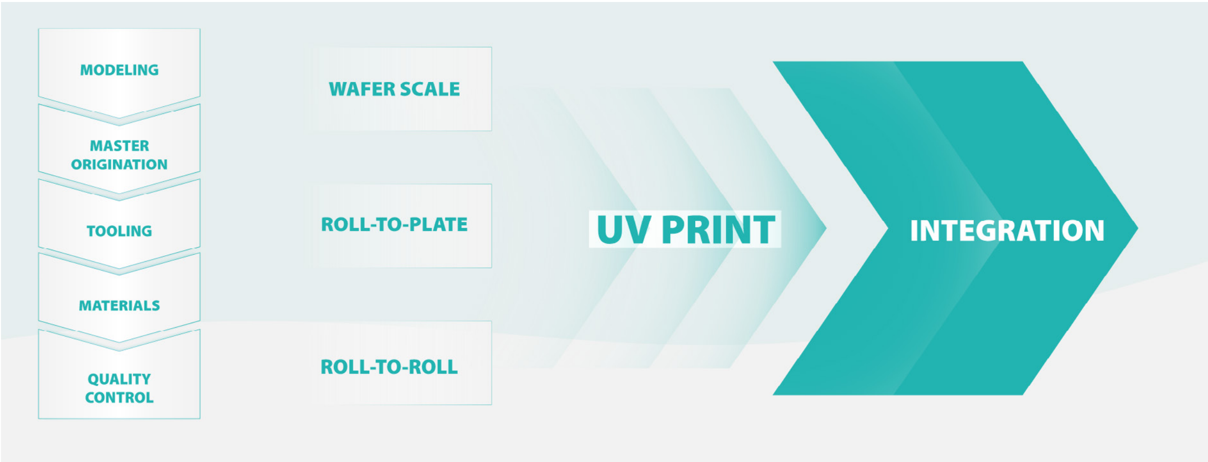
Introducing PHABULOμS

Unique selling proposition

PHABULOμS 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.



PHABULOμS'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.

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Introducing PHABULOμS

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 **("PHABULOμS Project")**.

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

- Implement the PHABULOμS 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 PHABULOμS 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 PHABULOμS Project.
- Represent the interests of the PHABULOμS Pilot-Line community on a national and international basis.

The Pilot-Line Front Office (PLFO) of PHABULOμS – 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 through Dr. Rolando Ferrini at rolando.ferrini@csem.ch.

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 PHABULOμS 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

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Introducing PHABULOμS

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State-of-the-art Technologies

1 - Open design platform

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

The PHABULOμS Pilot Line design platform includes proprietary solutions for the design of free-form micro-lens arrays (FMLAs) based on customer specifications. Specifically, PHABULOμS 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.

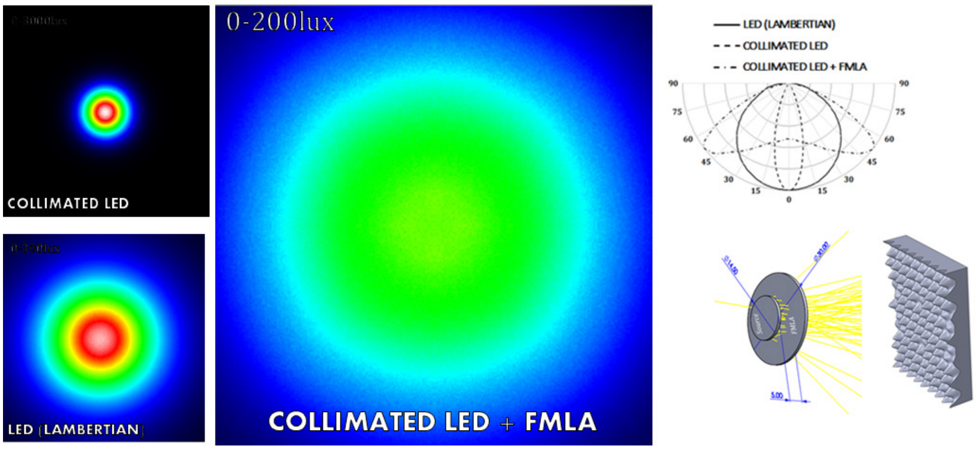

Figure 1: A narrow-beam LED is beam-shaped to a batwing LID (luminous intensity distribution) by a FMLA designed using the indirect design approach. Left) Far-field Illuminance distributions. Right-top) normalized candle-power plots. Right- bottom) ray-traced CAD models of the light source and FMLA.

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.

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State-of-the-art Technologies

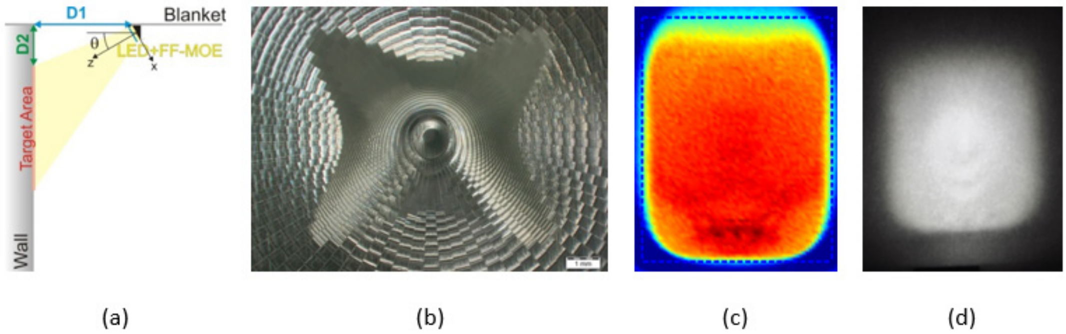

Figure 2: Asymmetric wall-wash lighting solution designed using the direct design approach. a) Schematic illustration of the optical system. An LED light source on the ceiling should homogeneously illuminate an oval target area on the wall. b) Designed the FMLA. c) and d) Predicted and measured illuminance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

Design for manufacturing – The PHABULOμS design toolbox comprises commercial design and simulation software tool such as ZEMAX, LightTools, LucidShape, Light Trans, etc. coupled to enabling CAD modelling solutions (SolidWorks, CATIA, AutoCAD, Rhinoceros & Grasshopper, Resurf, etc.) and custom-made scripts (Phyton, MATLAB, etc.). With this toolbox, the PHABULOμs 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.

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2 - Origination: form accuracy & surface quality

PHABULOμS innovative technological offer – The large scope of applications targeted by PHABULOμS 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 PHABULOμS Pilot Line offers an extensive selection of origination technologies including additive and subtractive, mechanical and laser-assisted, mask-based and maskless. Specifically, the PHABULOμS 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 patent pending technology available in PHABULOμS 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. The table below compares DPI™ to three well-known free-form machining technologies namely Slow Slide Servo (SSS), Fast Tool Servo (FTS) and Diamond Micro-Milling (DMM).

	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

The COMPAS proprietary isothermal micro-forming process enables the replication of DMM FMLAs (for e.g. polarity reversal) in very short times compared to e.g. electro-forming. Currently limited to 40 mm tool diameter, the COMPAS technology will be upgraded to 120 mm diameter tools.

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State-of-the-art Technologies

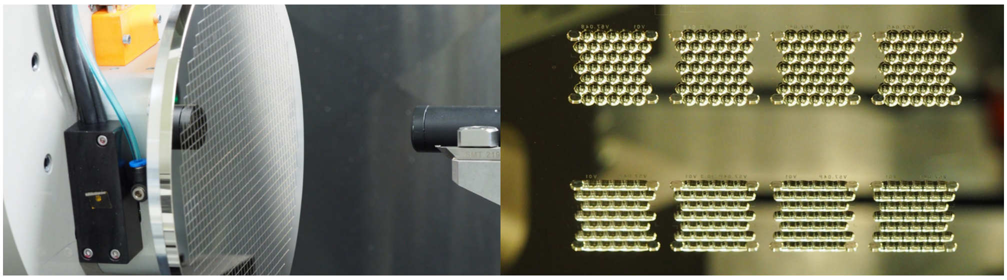


Figure 4: Diamond micro-turning: Dynamic Part Indexing (DPI™) for Micro lens arrays (MLAs). Left) 8" prototype MLA wafer. Right) Close-up view of machined FMLAs on a 8" wafer.

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.

LMM 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 PHABULOμS. LMM makes it very attractive as an origination process for large-volume UV-imprinting replication.

The LMM equipment available in PHABULOμS is highly automated on (4" maximum) wafer-scale with a throughput of ~ 1 cm^2/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.

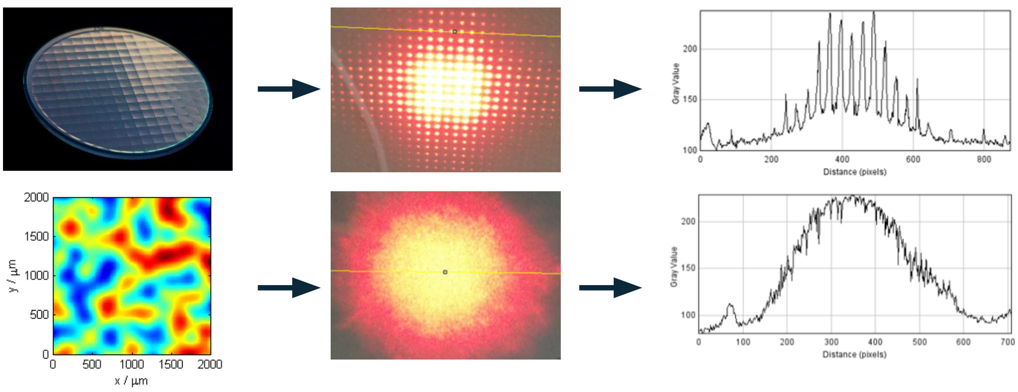


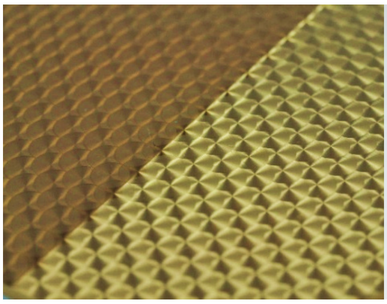
Figure 5: Laser micro-machined FMLAs (PRIME Beam-shapers). Top) Lens Array with Low M2 Beam. Bottom) PRIME with Low M2 Beam).

State-of-the-art Technologies

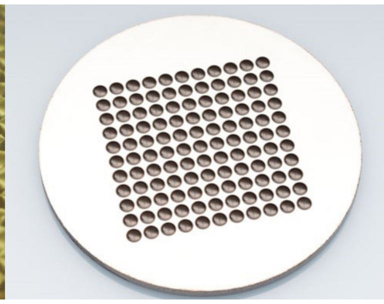
Two-Photon Absorption (TPA) enables full three-dimensional structuring of arbitrarily complex models with a resolution in the submicron range. Although well-established on a laboratory scale, industrial level throughput has not been demonstrated yet.

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) – PHABULOµS 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.

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State-of-the-art Technologies

PHABULOµS ambition – The PHABULOµS 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	PHABULOµS 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 60º** (with metrology) Extend COMPAS capability to handle **120 mm** diameter tools (currently 40 mm)
Laser micro-machining	Increase throughput by a **factor of 2** Increase clear aperture **from 2 to 4 inch** Increase maximum angles **from 30º to 60º** (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 PHABULOµS 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.

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State-of-the-art Technologies

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.

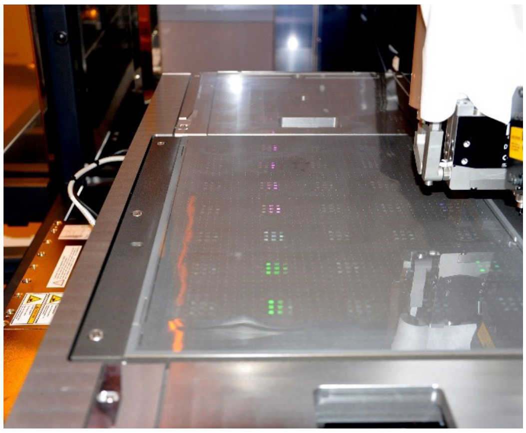

Figure 7: Production of flexible embossing tools for roll-based UV imprint replication.

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.

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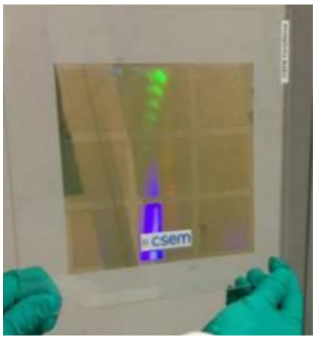
State-of-the-art Technologies

Main advantages of PHABULOμS 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 100 times, and is thereby highly cost-effective.	Cost-effective and reproducible replication of master with minimal quality variation.
Industry-compatible	The possibility to tile multiple products on the large-area soft stamp enables high-volume production volumes.	High accuracy alignment (< 500 μm accuracy on the plate to plate positioning in reel surface layout) of the nickel tools and the embossing reel. A high number of nickel tools can be manufactured from a single master.
Step & Repeat imprint method has accurate positioning within 5μm	Roll-to-Plate imprint alignment accuracy from large-area soft stamp to substrate is well below 100 micron. Developments ongoing for soft-stamp to substrate alignment accuracy below 10 μm.	Chemical modifications of the Nickel replication reel for extension of the reel lifetime. High resolution and good replication fidelity.
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.	Good mechanical durability and chemical resistance of the tool. Cleaning of nickel tool for extension of the reel lifetime.

The ambition of PHABULOμS is to produce replication tools with areas up to 200 mm round for wafer-scale, 600×1000 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.



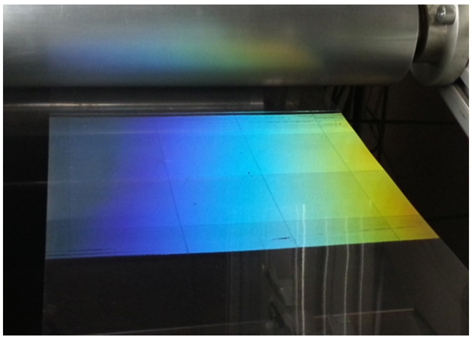


Figure 8: Left) Plasmonic gold nano-structures fabricated with a step-and-repeat UV casting process, resulting in a 15x15 cm^2 sample. Right) Sheet with a 2D diffractive nano structure for enhanced in coupling for thin film photovoltaics.

State-of-the-art Technologies

4 - Large-area UV imprint replication

PHABULOμS 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	600x1000 mm^2 plates	500mm web width* (production line) 240 mm (R&D line)**
Maximum surface area in PHABULOμS	300 mm diameter**	600x1000 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 PHABULOμS	30000 wafers**	2000 plates	200 km/line (production line) 25 km/line (R&D line)

**480mm micro-structured width; ** With the production rump-up planned by PHABULOμS partner Suss Micro-optics (Excellence Center)*

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State-of-the-art Technologies

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 is 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 PHABULOμS Wafer-scale UV imprint replication technology	
Maximum structures height	500 μm
Minimum residual layer thickness	≈ 20 μm
High alignment accuracy of components	1 μm in wafer plane and 3 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

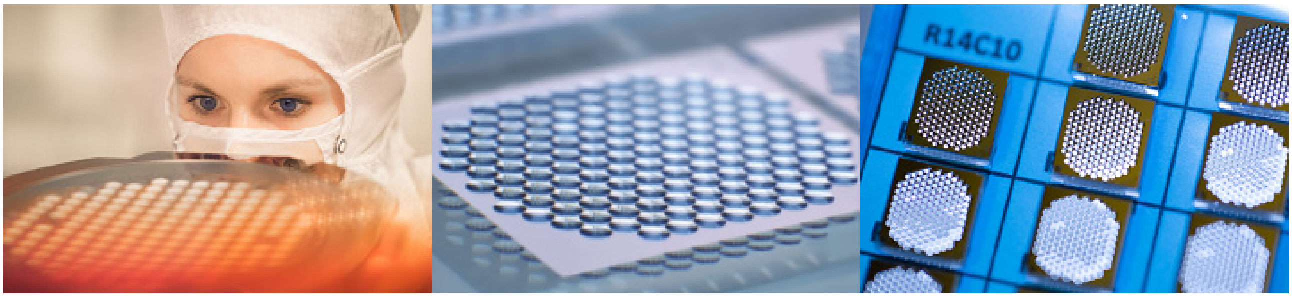

Figure 9: Micro-imprint fabrication of micro-optical elements. Micro-optics is fabricated on wafers of 200 mm diameter and separated by dicing. Each micro-optical element has more than 100 channels to realize its functionality. The multichannel concept together with free-form optical design allows to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

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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 is a proven process for textures well below 100 µm height, shrinkage around 5% and a yield between 50 to 75%. The current alignment accuracy is ±200 µm.

Main advantages of PHABULOµS R2P UV imprint replication technology	
Imprint textures on discrete substrates	Replication of multiple products per imprint cycle possible
Re-usable flexible stamps	Replication quality (50 nm bars and AR slanted gratings)
Wide range of structure heights (50 nm - 500µm)	Compatible with 100 µm (height)structures
Imprint speed up to 10 m/min	Mass production Gen3 line running (display applications)
Extremely large area imprinting (up to 1 m²)	Gen5 size imprint modules available mid2020

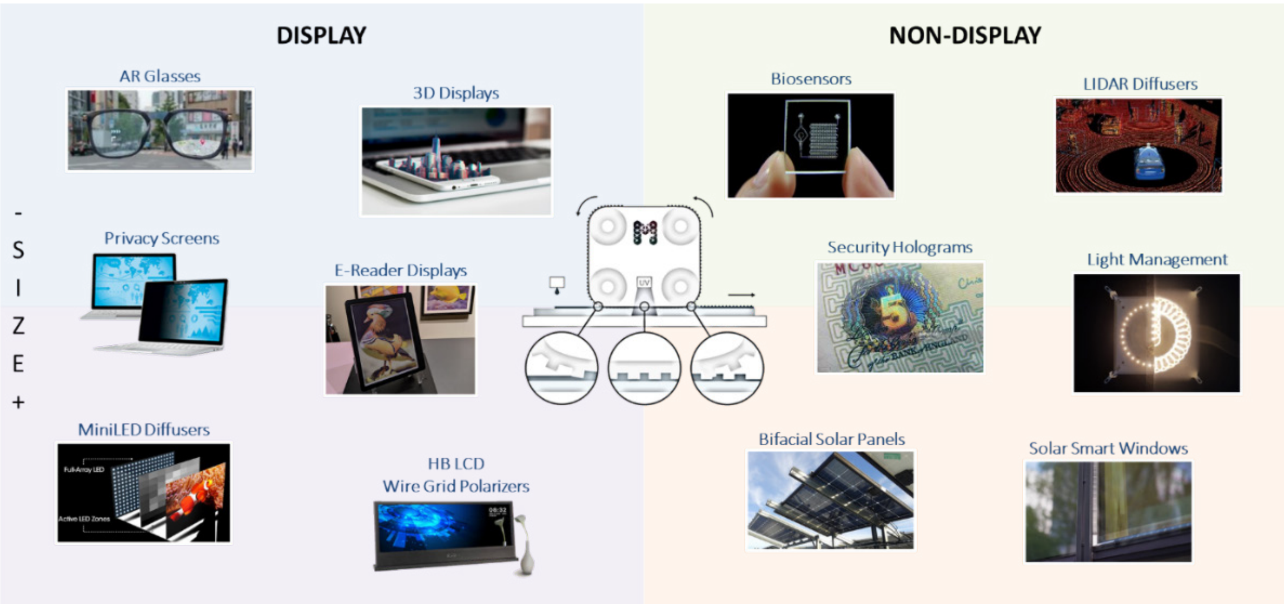

Figure 10: The R2P technology can be used for different applications where precise micron or nano-scale structures are need at high volume and commercially viable costs.

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Roll-to-Roll (R2R) UV imprint replication has demonstrated high-resolution micro and nano-structures via moulding/ imprinting with length scales far below those associated with the traditional manufacturing technologies of plastics (e.g. printing, injection moulding). This technology has been used for the high-throughput fabrication of optical structures like grid polarisers, micro-lens arrays and plasmonic structures. A detailed comparison between R2R UV imprint and two common competing replication technologies is presented in the table below.

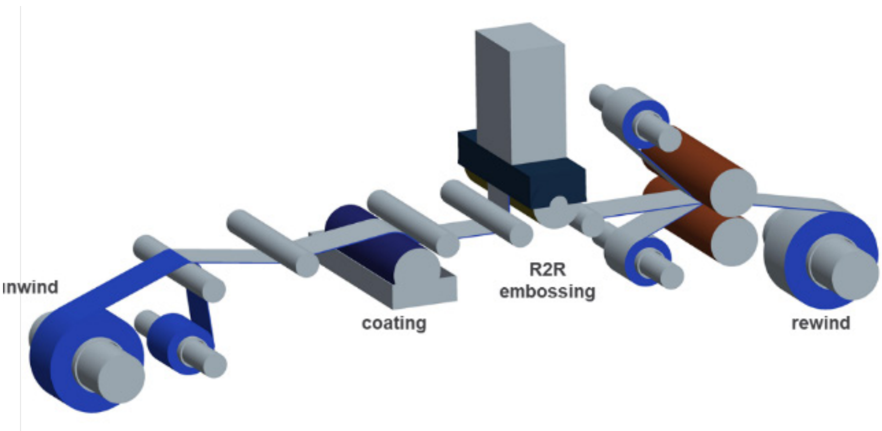

Figure 11: A schematic presentation of the R2R UV imprint process (Nanocomp).

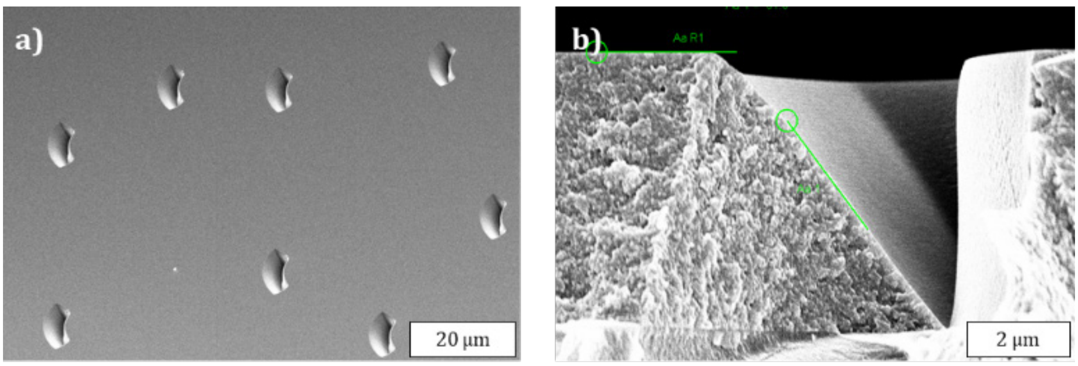

Figure 12: Top view (a) and X-section (b) SEM images of prismatic micro-structures replicated using PHABULOµS R2R UV imprint (Nanocomp)

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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

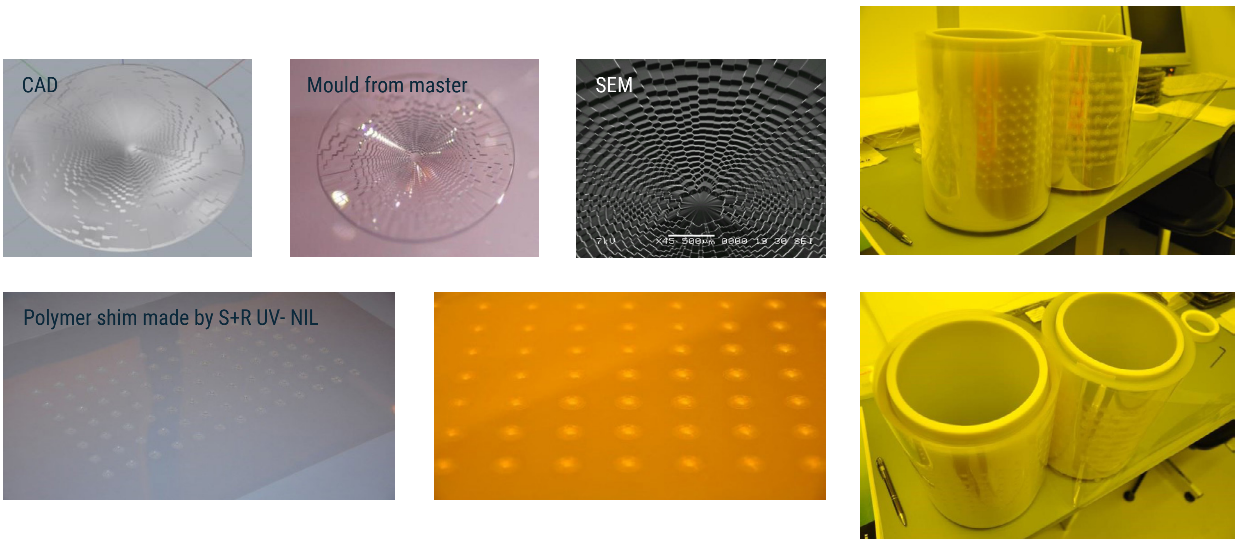

Figure 13: Mastering and replication of FMLAs by JOANNEUM Research Institute

State-of-the-art Technologies

Replication Technology	PHABULOμS 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 we have a proven process for textures well below 100 μm height, shrinkage around 5% and a yield between 50 to 75%. Current alignment accuracy is ±200 μm. Within PHABULOμS 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. PHABULOμS 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

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

State-of-the-art Technologies

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, 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

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State-of-the-art Technologies

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.

PHABULOμS 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.

State-of-the-art Technologies

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

PHABULOµS 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.

PHABULOµS 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 PHABULOµS to offer the mentioned technologies in sheet-to-sheet and roll-to-roll configurations to support all customer and applications.

PHABULOµS offer of optical coatings:

Sheet-to-sheet	
Processes	Reactive magnetron Sputtering Magnetron PECVDReactiv e 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 SiOxCy 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)

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7 - Quality control

In order to ensure high quality FMLA components, the PHABULOμS 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 PHABULOμS Pilot-Line to overcome the limitations of current state-of-the-art quality control.

The PHABULOμS 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.

PHABULOμS 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

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 PHABULOμS 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.

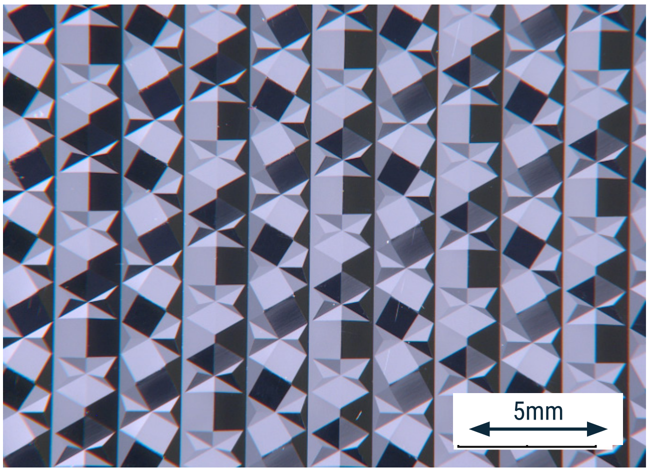

*Figure 15: Left) bending/rolling characterization.
Right) microscope picture of a FMLA*

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, CSEM has recently developed a 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).

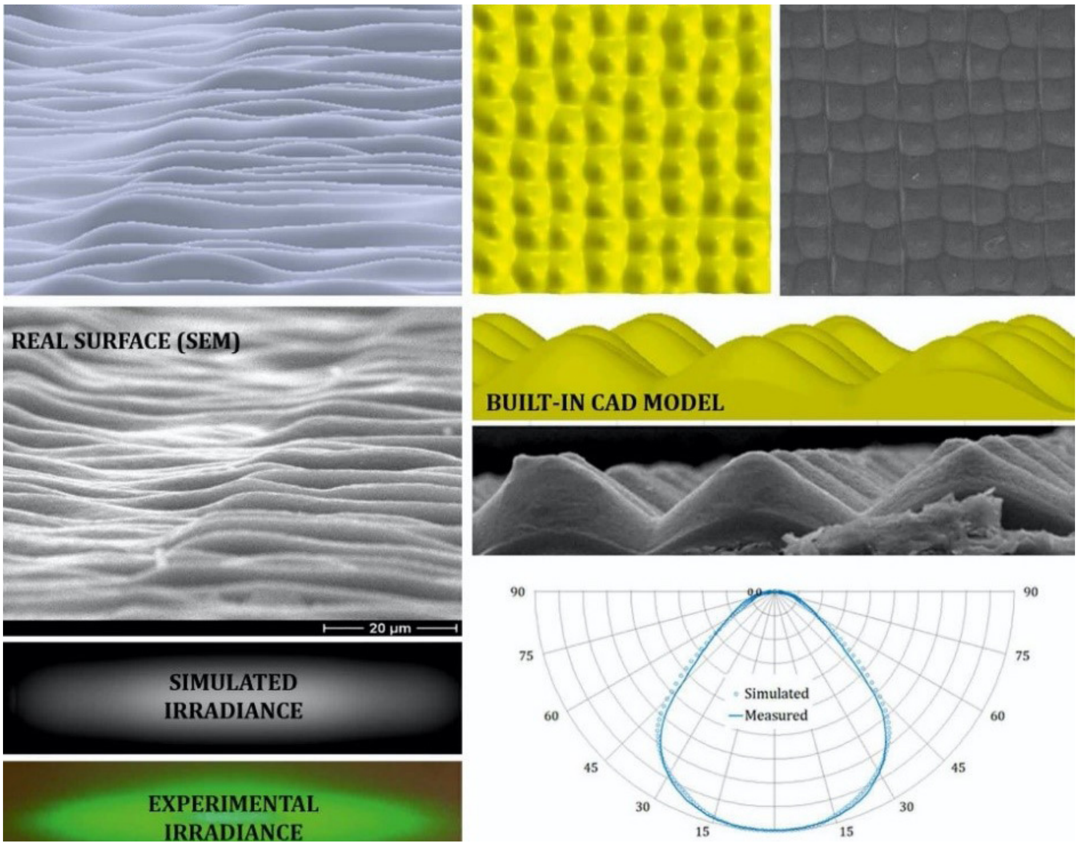

Figure 16: "Semi-empirical characterization method". CAD models and SEM picture and predicted versus observed performance (left) of a BrightView E1060 asymmetric diffuser. BrightView G-CG90 de-glaring foil (right). Predicted and measured luminous intensity of a de-glared OLED (bottom right).

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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 PHABULOμS quality control process.

Other important properties will be measured and reported including material optical properties, stability and large-area uniformity using PHABULOμS 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.

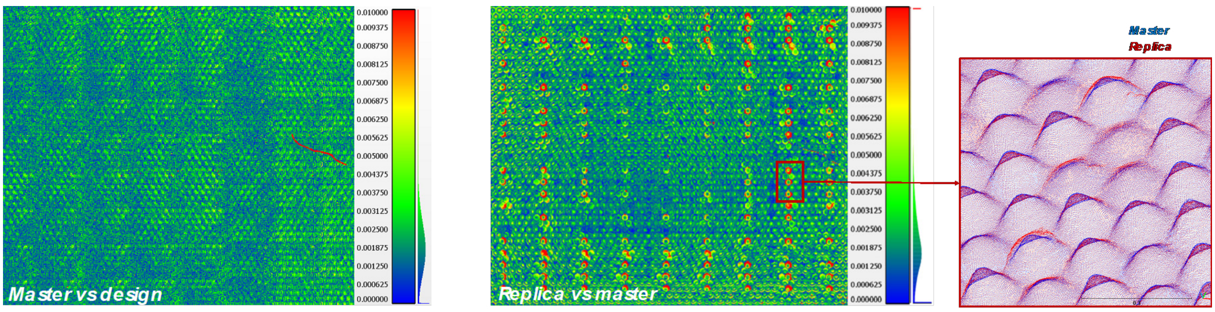


Figure 17: Surface analysis by CSEM: Left) The surface roughness of the Master is compared to the Design and is virtually identical to it. Right) the Replica is compared to the Master. The replica shows relatively good form accuracy, however localized large deviations observed. Software packages used, 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 PHABULOμS project.

State-of-the-art Technologies

Figure 18: S2S and R2R assembly machine examples by VTT.

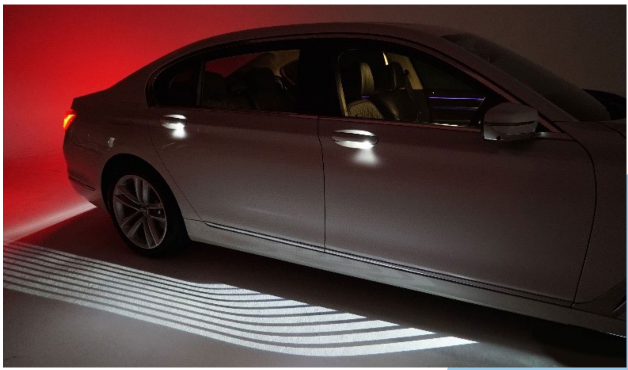
Top) S2S/R2R device assembly machine Datacon 2200EVO.

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

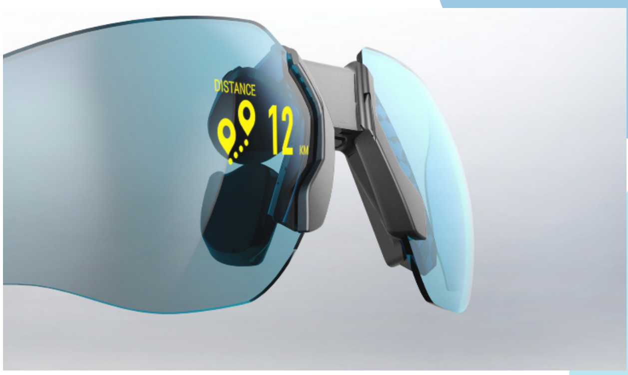
Bottom) New 2-arm 6-axis S2S alignment & assembly machine.

Market Applications

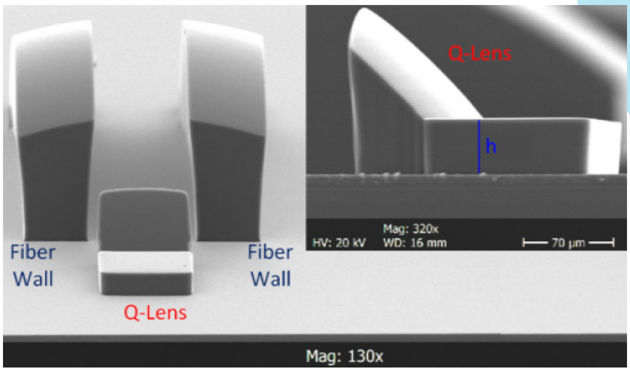
Various market applications for free-form micro-optics



Micro-lens arrays for lighting



Micro-displays for AR / VR / MR



Free-form optics for photonic integrated circuits PICs

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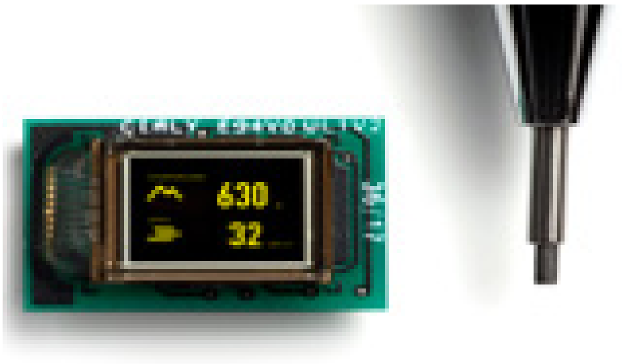
Market Applications

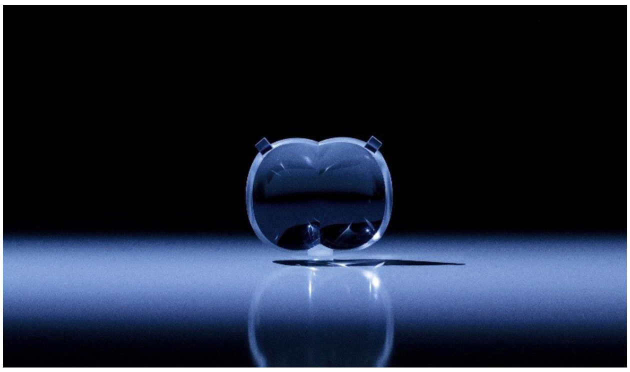
Automotive lighting



Micro-displays

Solid-state lighting

Luxury



Virtual reality

Transportation interior lighting

Market Applications

LIMBAK's advanced FMLAs for VR, AR & MR

LIMBAK is developing high-performance and innovative optics for Virtual Reality (VR), Augmented Reality (AR), as well as Mixed Reality (MR). LIMBAK is licensing its high-performance, patented optics, branded ThinEyes®.

One of the most advanced ThinEyes® concepts is based on free-form micro-optics, and is called TRENZA. This technology can lead to video-see-through MR headsets with the size of sunglasses and superior FOV and angular resolution.

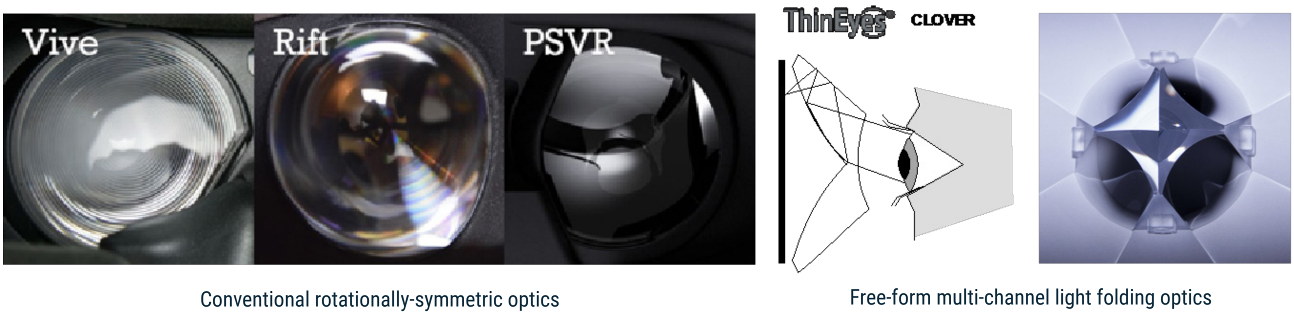


Figure 20: State of the art optics in commercial headsets are based on rotationally symmetric lenses (left). New headsets in 2020 are starting to be advanced optical trains, like the free-form multi-channel light-folding CLOVER lens (right), by LIMBAK

LIMBAK is one of the 6 use-cases of PHABULOμS. TRENZA is a super-thin (8-10 mm only) optical technology based on a set of free-form 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:

- High angular resolution: achieved by the use of a design technique, also patented by LIMBAK, named "SUPER RESOLUTION", based on adapting the shape of lenses to the special features of human vision and by the use of core TRENZA technology, "pixel interlacing"
- Allows the achievement of wide Field of View.

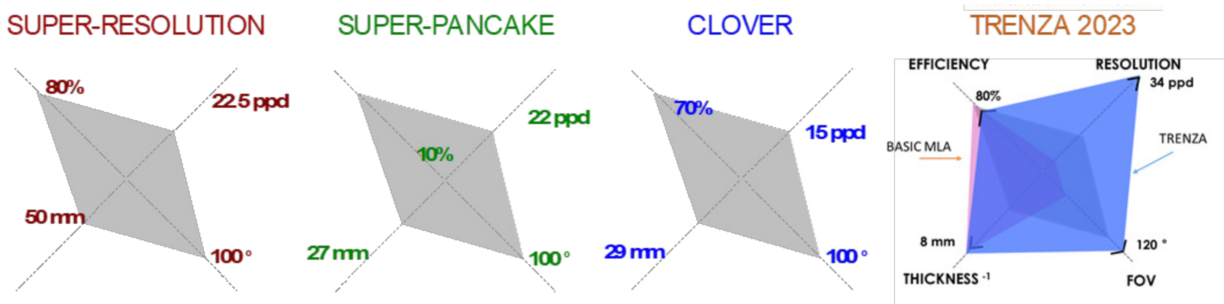


Figure 20: TRENZA, to be developed within PHABULOμS, benchmarked against the state of the art

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Market Applications

There are several variations of TRENZA that depend on the goal performance features and technological limitations. LIMBAK has designed one of these variations within the scope of PHABULOμS, observing the pilot lines manufacturing constraints expected after acceleration of manufacturing services.

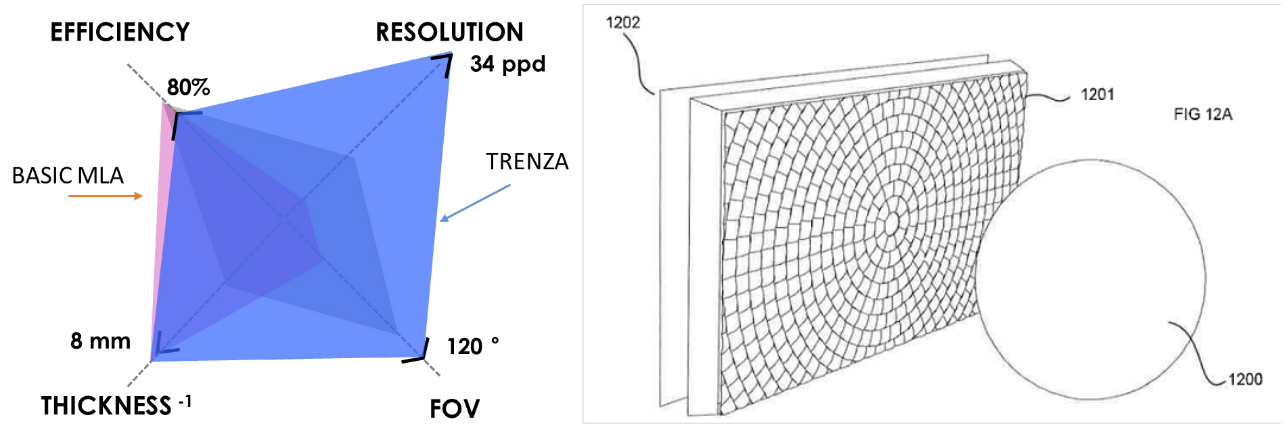

Figure 21 (Left) TRENZA FOV, resolution, size and efficiency (orange diamond) achievable with displays predicted for 2023, compared to those of the basic MLA (pink) and the conventional VR optics (grey). (Right) caption from LIMBAK's patent explaining one embodiment of TRENZA, where lenses form, shape and pitch are free and non-constant, respectively.

The MLAs of this design include 4 arrays of free-form lenses working in parallel, through ~ 300 optical channels.

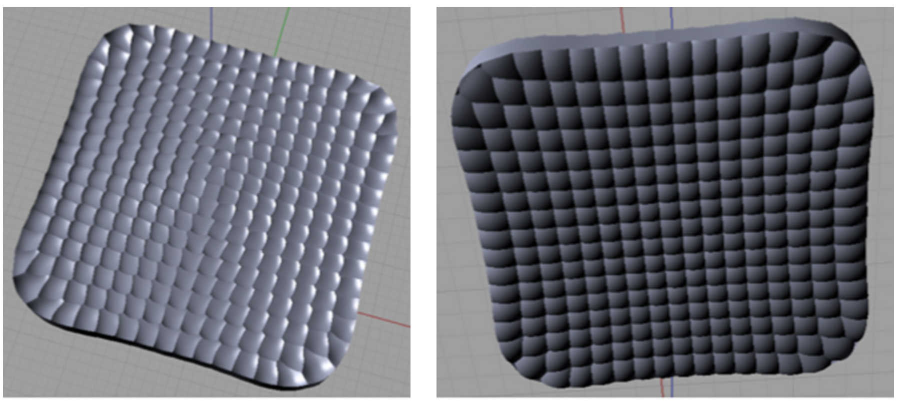

Figure 22: TRENZA 2-side MLA optical stage designed within PHABULOμS Pilot Line

TRENZA requires advanced optical manufacturing technologies. LIMBAK sophisticated designs for high resolution and wide FOV free-form micro-optics, in combination with PHABULOμS manufacturing capabilities will lead into MR technologies with a considerable market share by 2023-2024.

The unique features of TRENZA can be obtained via the unique manufacturing framework of the European Pilot Line PHABULOμS.

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