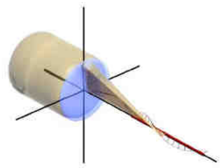
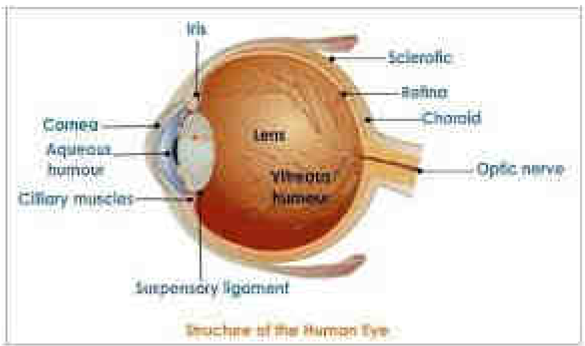
LightSwords project - main S&T results; foreground

Ambitions

The motivation for Lightswords project development was to deliver the novel solution for ophthalmology, when the presbyopia is the considered malfunction of human eye. The LightSwords itself is the nickname of certain optic structure being an object of investigation. The most common diseases associated with ageing is the decline in the quality of vision. Due to the mechanisms that occur in the human eye, its ability to change its optical power decreases at a rate of 0.2D per year. For those in their 50s, a minimal possible reading distance increases up to half a meter. This disadvantage, known as ***presbyopia*** makes serious difficulties in everyday life. The regular ophthalmic treatment is dealing with dedicated glasses, goggles, contact lens and eventually intraocular lens. When optic characterization is considered, the corrective lens are driven with demand for sharpness of vision for certain distance. For example, when glasses are considered, their optic characterization is fitted to correct the lost adaptability of human lens for accommodation (presbyopia and other eye dysfunctions). More advanced solutions are exploiting bifocal, pinhole, aspheric corrective lens principles.





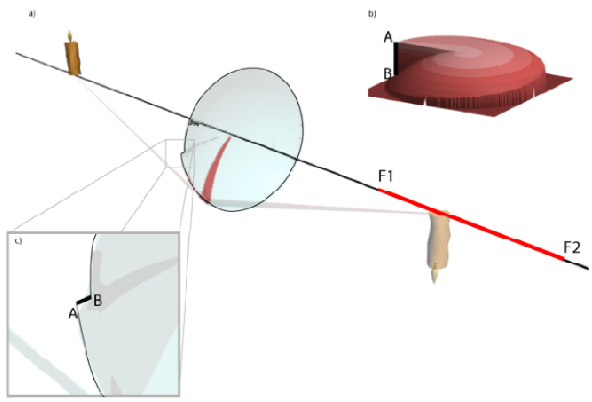
The people still active in their profession are facing more complex situation; the working area requires varying optic power i.e. manual writing and operating in extended length distance simultaneously. It is not uncommon for workers suffering presbyopia or myopia to wear **safety goggles over prescription glasses**: this practice is not only uncomfortable, but risky as well.

LightSWORDS aimed at developing and adapting existing technologies for high-quality low cost manufacturing of **a new type of asymmetric plastic lens to be applied in the correction of human eyesight**.

The innovative element of proposed solution is the novel **L**ight**S**words **o**ptic **e**lement - LSOE, where extended depth of focus is embedded in fixed structure geometry. **In contrary to bi- tri- and multi-focal lenses it provides sharp vision in every distance between 20 cm and the infinity, as if human eye ability to change the lens geometry due to required focus of vision would be preserved.** It shall be pointed here, that the optic eye characterization is here driven by extension of focus instead of vision sharpness.

That optic feature opens also possibility of its exploitation in other domains as optics for cameras; here it could eliminate the need for focusing mechanisms and improve vision in the starlight. That is why the secondary commercial target of Lightswords project points out the surveillance cameras.

The innovative optical element represents a **radical breakthrough** in white light imaging, as it is an **asymmetric lens focusing light into a narrow line segment**, contrary with respect to all currently used solutions which possess symmetry of revolution. It can be observed as an infinite set of infinitesimal angular sectors containing lenses with varying optical power from 0D to 3D (see the below figure). Such a optic structure provides acute vision corresponding for object distances from 25 cm (near vision-reading) to the infinity (far vision). The height of the sharp step, which is necessary to assure 3D of the optical power required to compensate satisfactorily the lacking accommodation, should not exceed the value of 25 cm, eventually 33 cm.



The LSOE element is static and does not require any movement and/or stressing while using. That makes it a useful solution in medicine practice. The theoretical features of LightSwords structure were well analysed for last 10 years. However detailed optic bench characterisation as well as human tests were not done. That was because of manufacturing difficulties (accuracy of optic surface extended to the continuous asymmetric surface – other words free surface - with embedded discontinuities).
The model of the refractive LightSWORDS lens was fabricated previously once with photolithography in sol-gel Ormocer^{TM} photoresist deposited onto a 1mm thick glass substrate of 25.4 mm diameter. However, the material properties were not relevant to the industrialization.

Thus the milestone for further development of that promising technology was to develop the manufacturing technology, which would allow to start up the LightSwords structures fabrication for ophthalmic applications.
Having in mind mass production of LSOEs, the well-known polymers injection moulding and hot embossing were selected. However still challenging was to manufacture the forming part of mould within required dimensioning, accuracy, surface roughness. To win over the prospected technology difficulties, outstanding technologies were selected. The first one was the multi axial milling of free surface, where the tooling would result in the high “optical” accuracy combined with surface quality reaching finishing without any additional treatment. The second approach was the novel one, where the holography experience would be extended to micro mechanic technology; to proceed the grey scale laser lithography for thick (>1µm) photoresist was selected and the mould forming part was to be obtained with electro-chemical treatment – namely nickel thick galvanization.

Thus manufacturing reliability within prospected technology window has been proven to be a key factor for prospected Lightswords exploitation.

The main goal of LightSWORDS Project was to set up a precise and highly repetitive technology for cheap mass production of such lenses. Achieving requested imagining quality was assumed as a condition for LightSWORDS lenses concept shifting to the stage of ophthalmic development and prospected practice.

Scientific & Technical Objectives

The leading objective of LightSwords project was to develop and to validate the manufacturing methodology for the production of asymmetric LightSwords structure. The focused mass production technology was selected as polymer mould injection and hot embossing. For complementarily of approach, direct micromachining of Lightsword structure in the polymeric material was considered. The crucial stage of technology was the development of moulds forming parts: die, stamp etc within required dimensioning regimes, accuracy and roughness. The suitable manufacturing methods were selected as follows:

a. Grey scale laser lithography on the thick photo-resist. This technology required Laser lithography machine with grey scale etching function, where photoresist thickness could reach 50 µm. That technology is an innovative in the sense of expected process parameters (technology window) and area of exploitation (mechanics). The expected results were ability to manufacture sharp steps on the mechanical elements (filleting where, radius is close to 0 and slop of step close to 90^0)
b. EDM (Electro-Discharge Machining) technique. That approach assumed the exploitation of regular free forming milling within high accuracy limits and finishing process for spark ablation of the material including electro polishing capability.

For technology validation: geometry checking of mould forming parts and LSOE structures were prospected and optic characterization of obtained polymeric samples on the optic bench.

The primary assumed geometry criteria for both LSOE structure and forming tools were following:

- Thickness measured along the optical axis: 50 ± 0.2 µm (measured on a significant set of samples, at least 10).
- Accuracy of profile: 0.1 µm tolerance with respect to the theoretical 3D model (measured on a significant set of samples, at least 10).
- Step profile sharpness: maximum deviation from 90° below ±2° (measured on a significant set of samples, at least 10).

The selected assessment tool was profilometer.

Considering optic validation criteria were following:

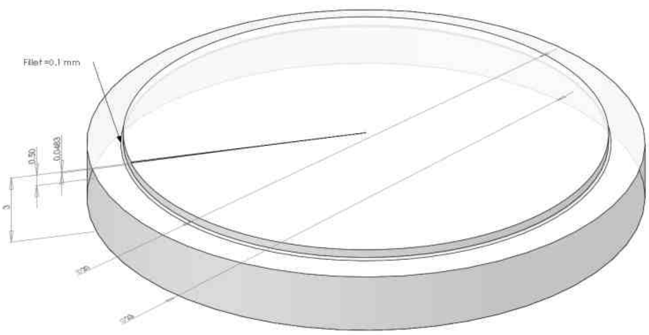
- Optical power: continuously varying between 0D and 3D defocusing correction (sharp imaging between infinity and 25 cm focal distance)
- Resolution: - angular 1’
- Focus depth: 9%
- Achromatic imaging properties; resolution decrease: <20% on the visual range sides

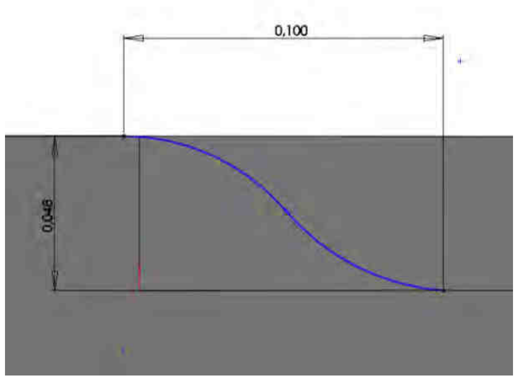
Technology barriers and applied contingency actions

Two criteria for technology acceptance were selected:

- Ability to manufacture the almost flat surface with slowly varying curvature,
- Ability to manufacture the sharp edge (both concave and convex) within 0 to 50 µm step high

To assess selected technology limits, the 0-0,5D LightSwords structure was selected, where almost flat surface is disrupted with sharp step of height 0 - 50 µm. The selected material for targeted lenses was PMMA.





When considering the machining approach, the ability to replicate free surface with the sharp step had to be investigated with high technology equipment. It shall be kept in mind, that disrupted surface is continuously changing their curvature from the side of structure just to the centre (zero curvature) on both sides of step. The issues, how “sharp” the step could be machined or how extended will be the transition zone were investigated with DT (Diamond Turning) technology. Having in mind the prospected difficulties, the optic parameters sensitivity analysis against manufacturing imperfections (edge filleting and step ramp) were proceeded as a part of research.

Following optic features sensitivity analysis versus possible manufacturing imperfections, the manufacturing constrains assumed during project set up were updated:

a) Maximum surface offset (tolerance of surface machining):±0.5µm; however in no point of the lens this deviation should be greater than 2µm.
b) Roughness of surface: $<R_a$=0.15µm

Step transition zone: ≤ 0.1 mm: +/- 50µm both sides off the step.

The grey scale laser lithography process was the virgin one, when expectations for Lightswords structure were to be manufactured. The former experience were extended, but for thin photoresist (1 µm). Nevertheless the sharp edge availability was observed as a straightforwardly achievable, while capability to obtain surface with the slowly varying, small curvature had to be investigated.

The series of experiments, extended query on specific topics related with considered technologies and finally “face to face” discussions with companies involved in the laser technology development was the basis for certain contingency actions. Following Consortium internal discussions as well as in the consultation with Project Officer, the contingency plan was applied as follows:

- The primary technology selected was direct micromachining instead of EDM technology as a parasitic to the main stream of process.

- Due to the extremely limited availability of thick photoresist (available composition, homogeneity for requested thickness) that technology line was investigated only partly. It was decided to extend knowledge with down-top strategy in line with available possibilities i.e. photoresist thickness. That is to start with photoresist of available thickness (finally upto 10 µm instead of 50 µm) and 8 bit grey scale instead of 11 bit grey scale.
- To compare the mould injection and hot embossing technology, Consortium decided to manufacture additional hot embossing mould: in this way the same structure obtained with two different mass replication technology was able to be compared.

Technology development results

The technology assessment was done with geometry measurements of forming mould elements and fabricated LSOEs samples. The LSOE samples were randomly selected from mould injection and hot embossing series of production. To validate soundness of obtained results, first optic measurements of samples were done also on the optic bench and compared with theoretically predicted values.

The LSOE is not typical optic object and there is no standard measures for its assessment. That is because of its asymmetry combined with discontinuities. **Standard optics performance is typically evaluated in the best sharpness/focus plane. The performance of the imaging lenses in defocused testing setup is usually out of scope. The idea behind LSOE is not to provide the best possible image quality at certain plain, but to provide the "acceptable" sharp vision across considered depth of field.** Thus within the framework of LightSwords Project there was taken an attempt to adapt axis-symmetric lens quality criteria for LSOE system assessment purposes. It is worth to notice, that here the quality factors may not be specified for one distinctive plane as for axis symmetric optics, but for several planes, which cover the depth of designed field range.

The extensive effort was spend by SKA and DAPP to properly set up optic measurements; both to use existing measures for optic evaluation and to quantify the novel features of asymmetric, nonlinear LightSwords structure. The first approach was set up. It was based on the concept of MTF and contrast evaluation. As the reference the theoretical model of eye (model – 60D) and interacting Lightswords structure was taken.

The virtual eye model (lens modelling the optical properties of the human eye, not LSOE) was free from chromatic and spherical aberration. However it shall be noticed, it is not true for human eye – LSOE optic system. In numerical modelling, the same LSOE design was used for all considered wavelengths (red: 632nm, green: 532nm, blue: 473nm).

The investigated distance was 0,25 …10 m. The evaluated parameters were considered as

- MTF (vertical and horizontal 10 to 40LP),
- image similarity in percentage in the domain of image contrast resulting from MTF spatial distribution ,
- depth of field (qualitative approach)

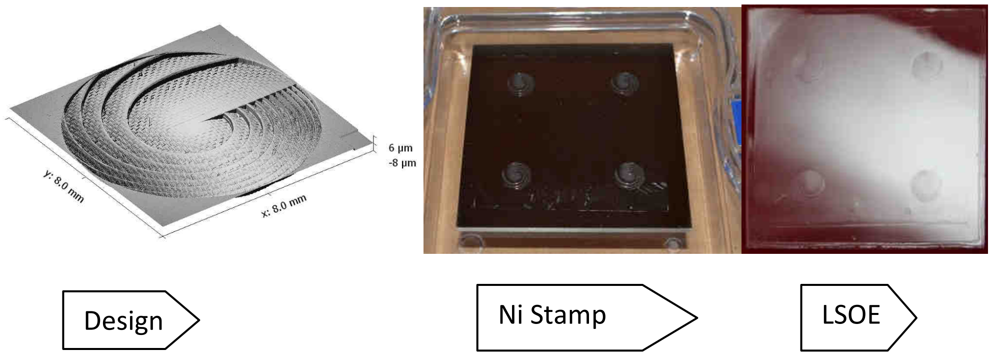
The Lightswords structures were than evaluated by means of quality measures. That was an additional effort during project proceeding.

Grey scale laser lithography technology line – hot embossing technology

The hot embossed process with laser lithography used for die manufacturing was most challenging issue in the project. Proposers believe, that approach is most feasible when advanced LightSwords optic structures would be considered for different ophthalmic dysfunctions treatment.

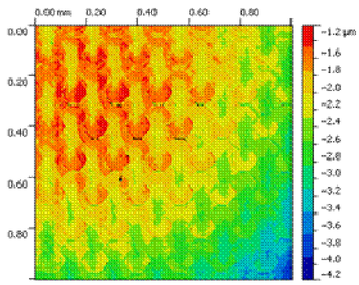
Finally that activity was aimed to proof, that the technology line based on the grey scale laser lithography processed on thick photoresist and followed with thick galvanization of mould die would allow to obtain the hot embossed LightSwords structures.

Considering technology limits, the selected material for final production was PMMA, the grey scale was limited to 8 bits and the thickness of photoresist was set to 10 µm. To reach the reference base set to power optic 0 – 3D within assumed thickness of photoresist, the dedicated LSOE was designed.

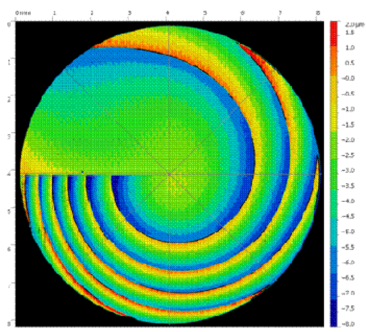


The stamp with four cavities was obtained with the 8 bit grey scale laser lithography process followed with 2mm thick Ni galvanization process. The samples were embossed in the 3 mm thick PMMA sheets.

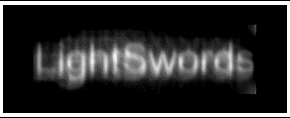
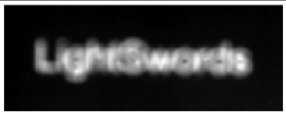
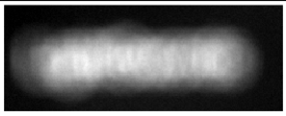
The randomly taken hot embossed plate was measured for detailed assessment of obtained roughness and optic surface deviation.



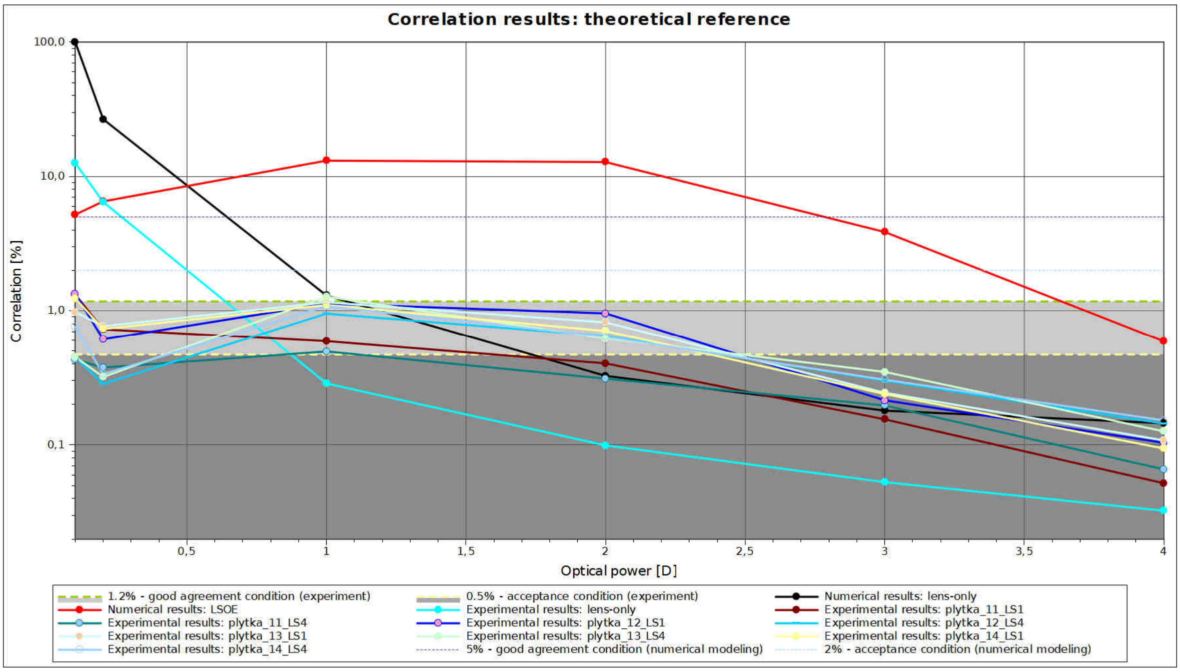
The roughness of forming surface for LightSwords structure was kept within R_a = 0,14 µm and corresponding embossed optic structure – within R_a = 0,13 µm. Both values are out of expected limits; the reason was the appearance of “scales” originated from stitching phenomena, which occurred during photoresist exposing - see map on the side. When the exactness of LightSwords structure mapping versus the theoretical one was evaluated, it was kept in assumed limits. However one shall consider the overall thickness of structure (less the 10 µm), and the relative error was too high. The step transition zone was well inside of assumed limits of acceptance.



The optic characterization of samples disclosed, that even the geometry of LSOE was out of assumed limits, the extended depth of focus could be easy identify – see table below.

Optical power correction	**Result -** Plate4_LS1	**Result -** Plate4_LS1	**“Presbiopic eye”**
0.1 D			
1 D			
3 D			

LSOEs obtained with hot embossing for mould stamp manufactured using laser lithography and galvanization do not provide acceptable optical performance and imaging quality. There are observed significant deviations from the reference profile, originated from manufacturing process, and brick pattern, which reduces the transparency and it is responsible for ghost images.



Even not meeting expected criteria, the results are promising.

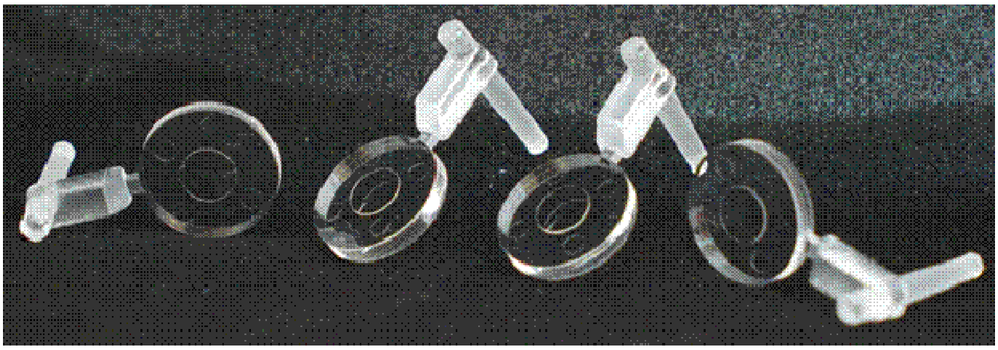
1. It was confirmed, that the grey scale laser lithography is well suited technology for sharp steps forming; that is “sine qua non” condition for advanced LightSwords structures.
2. The roughness and loss of shape is correlated with exploitation of low level grey scale laser lithography (8 bit). It may be improved with 10-11 bit grey scale exposure.

To conclude, the grey scale laser lithography was identified as the well suited and possible to exploit for advanced LSOE. Consortium Participants – in particular CMS, SKA and WUT are progressing their development behind time limits of LightSwords project with:

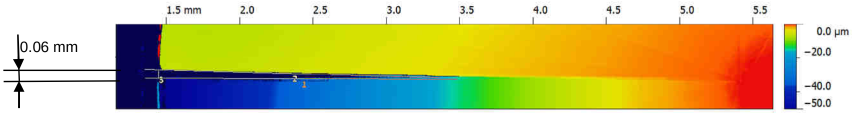
- **Thick photoresist development method**
- **Grey scale laser lithography process programming including hardware configuration modification.**

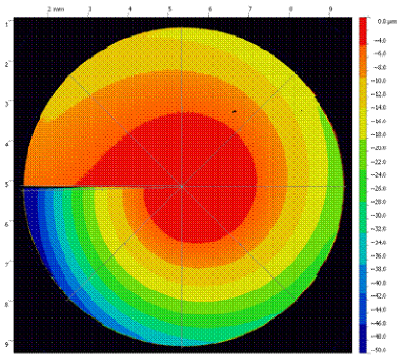
Micromachining technology line - Injection moulding

The direct machining of moulds often assisted with EDM for particularly fine geometry finishing is well known approach. Here the objective of LightSwords project was to reach the assumed level of geometry quality – in particular free surface milling with slowly varying close to 0 curvature and sufficiently sharp geometry of step. Additional issue to solve was the proper surface finishing. With few attempts the forming surface of mould was machined and mould – assembled. The pilot production was done. For assessment four randomly selected lenses were chosen.



The obtained roughness of mould forming surfaces as well as for all measured lenses was within assumed limits: below R_a=0.15μm. The forming surface was done with 2 μm exactness as predicted during design. The LightSwords samples exactness were in principle within range of 1 - 5 μm, when referenced to forming surface. The step transition zone were obtained within assumed limits and it was extended upto 60 μm. The selected samples of LightSwords structures were an object of further optic characterization.

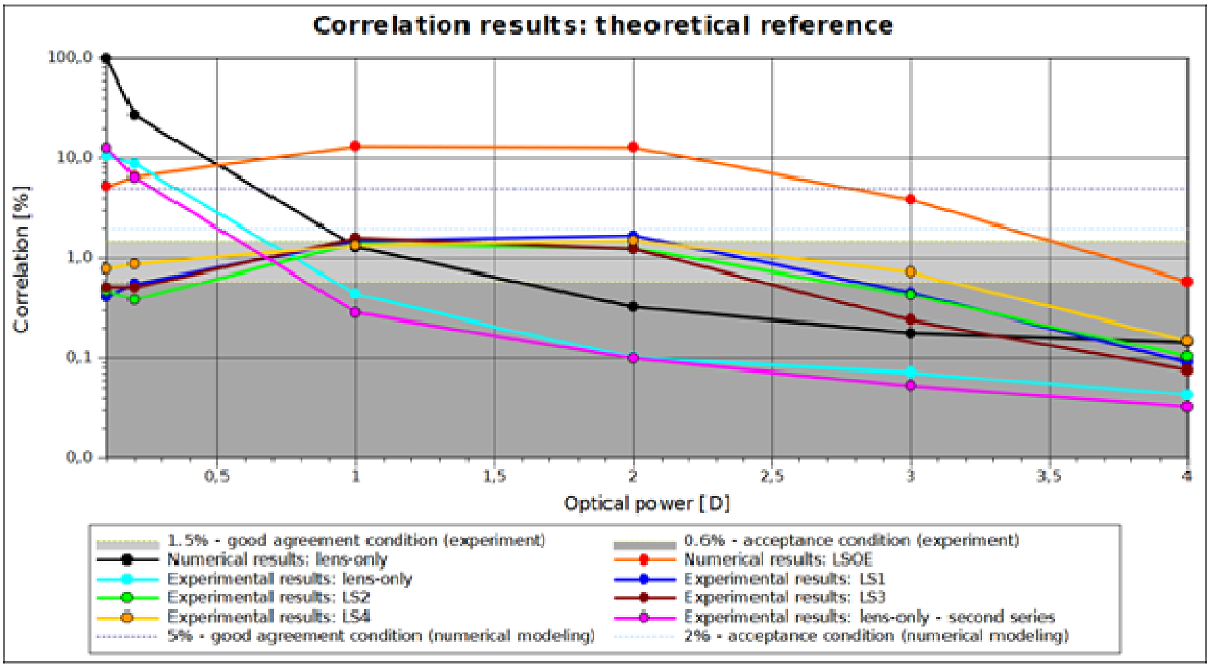




Similarly to geometry assessment, the samples were selected randomly from pilot production. First the qualitative assessment was done with imaging of label LightSwords. Then following MTF and contrast measurements, the quality measures were calculated in the form of correlation characteristics. The reference was considered as values obtained from theoretical model of produced LSOE.

"LightSword" labels visibility		
Structure (sample)	**Optical power correction**	**Result**
LSOE1 (LS1)	0.1 D	
	1 D	
	3 D	

Even the LightSwords effect is well observed on the label test, the full characterization of obtained samples gives information, that expected acceptance level is obtained in the limited range of 0,8 to 2 D. However the vision improvement is well recognized when violet/blue or black characteristic is compared with LSOE (navy, brawn, green, yellow).



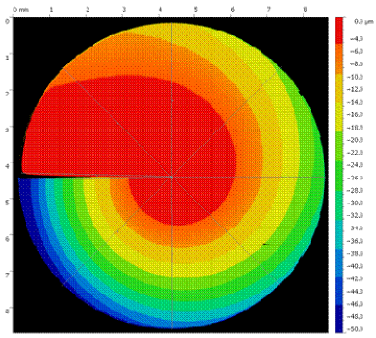
According to CMS experience in the injection moulding, the injected moulding LSOEs may be still improved with reference to theory with smooth modification of injection technology window.

To conclude, the injection moulding technology line with micromachined mould met the expectations of Consortium as satisfactory with quality and efficient in the mass production – short injection cycle.

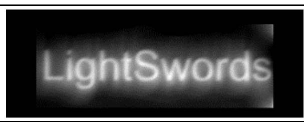
Micromachining technology line - Hot embossing

Following promising results obtained with micromachining for injection mould fabrication, Consortium decided to use the same technology for hot embossing tool development. That technology is particularly well suited for short series production, where process cycle is not the most important decision factor. Thus dedicated stamp was manufactured and LightSwords structures were embossed in the PMMA 3 mm thick sheet.

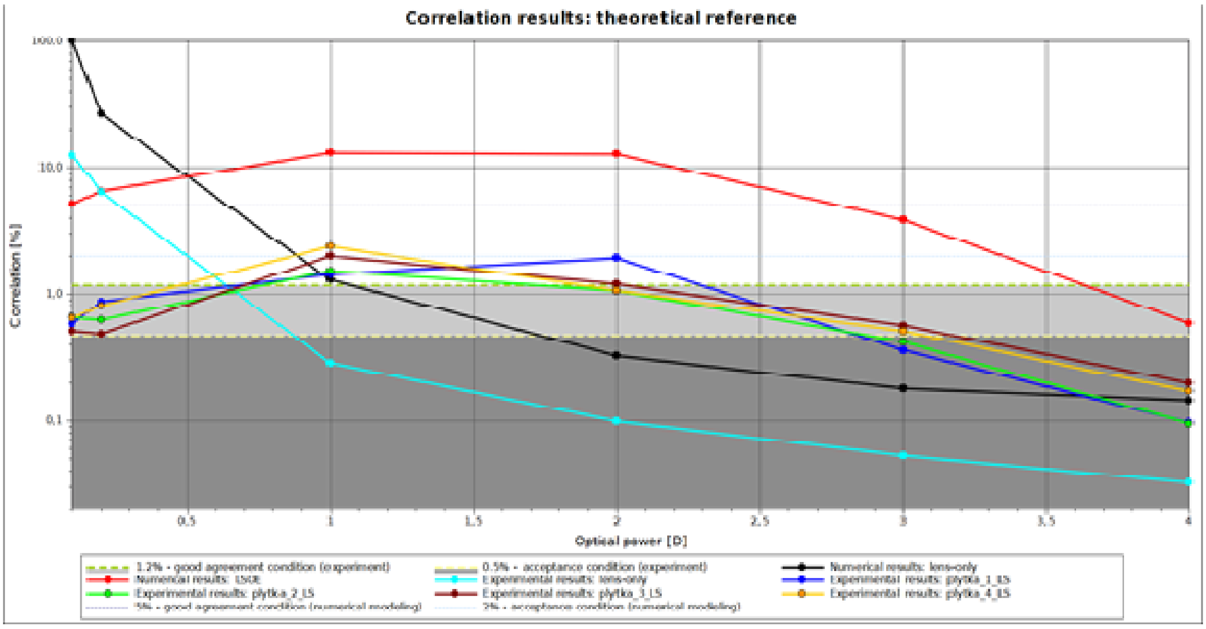
Roughness values R_a for all measured lenses were close to 0.018. This was higher than R_a value for stamp (0.010), but they are still much lower than expected limit which is R_a <0.15. The maximal deviations from reference (theoretical) profiles were not more than 2.6 µm; it is slightly above assumed tolerances, but still possible to scale down with better fitting of hot embossing technology. Finally step transition zone was measured. It was extended upto 70 µm and some small gas cavity appeared possibly because of the lack of venting.



The optic characterization gave good results. The label visibility was confirmed with qualitative characterization.

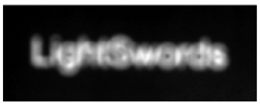
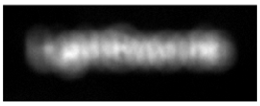
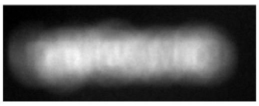
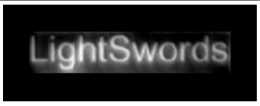
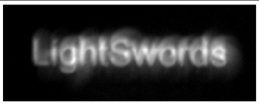
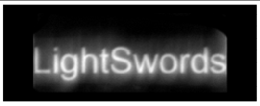
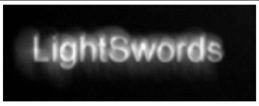
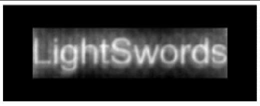
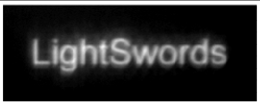
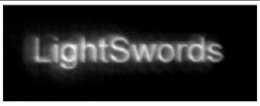
“LightSword” labels visibility		
Structure	Optical power correction	**Result**
LSOE1 (plate_1_LS)	0.1 D	
	1 D	
	3 D	

The expected acceptance level is obtained in the limited range of 0,5 to 3D.



To conclude, the expected technology parameters were reached for technology, where diamond turning micromachining for mould development was used. Both mas production technologies were accepted for further exploitation, however the injection moulding should be better fitted to technology window.

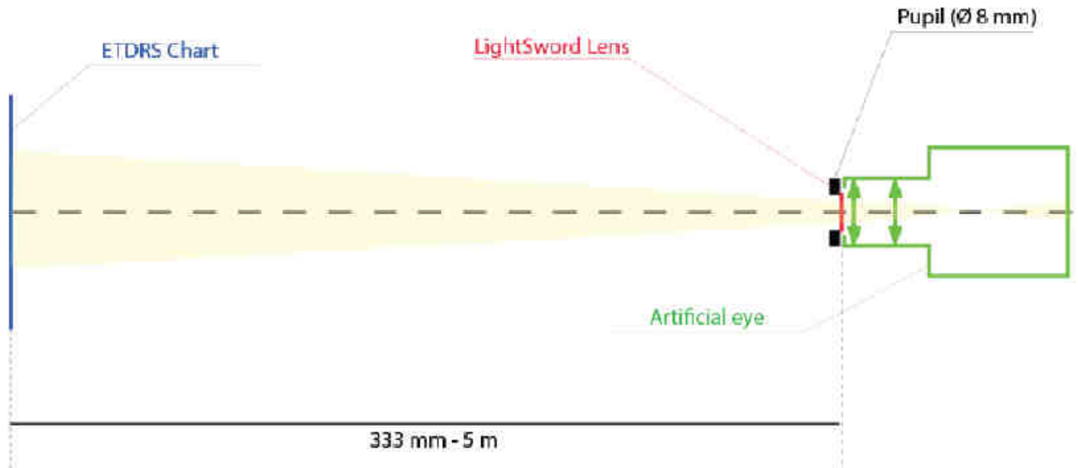
Approach comparison by optic

	5m (0.2D)	1m (1D)	0.5m (2D)	0.33m (3D)
„presbiopic eye”				
LSOE_DM				
LSOE_IM				
LSOE_EM				
LSOE_ELG				

Where:
LSOE_ DM: direct machining in PMMA
LSOE_ IM: injection moulding; mould done with direct machining
LSOE_ EM: hot embossing; stamp done with direct machining
LSOE_ ELG: hot embossing; stamp done with laser lithography

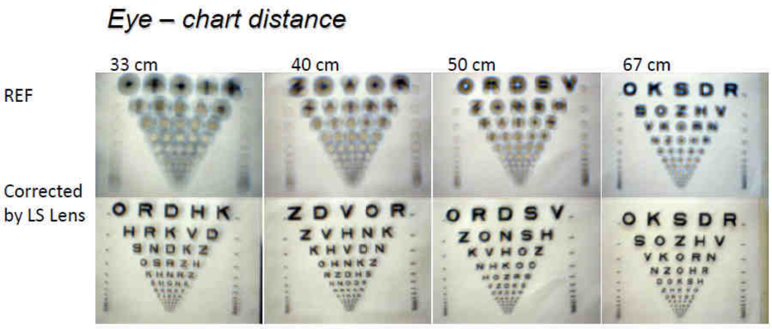
Optional tests – Visual acuity

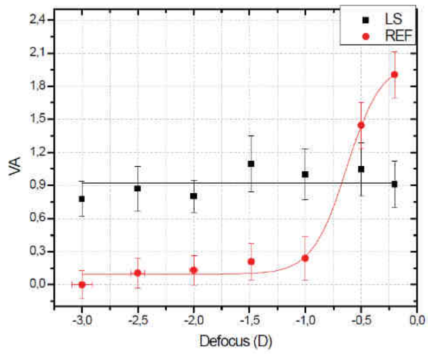
For ophthalmology purposes short tests campaign was proceeded on the basis of ERDS charts to evaluate the VA (Visual Acuity). The tests were done on the optic bench with artificial eye model, where LightSwords lens was obtained with injection moulding and with hot embossing.



Here the "presbiopic eye" was modelled with static 60D lens and correction lens was the LSOE.

The recorded ERDS imagining allows to consider, that the proposed LightSwords certainly improve/stabilize across distance the vision for those persons experiencing presbyopia – see REF row of ERDS visualisations versus row, where correction was introduced with LightSwords structure.





Those very preliminary tests were also confirmed by human voluntary. That results as obtained on the real LSOE samples are very first publish in the Biomedical Optical Express – OSA Journal in 2015.

<u>Foreground.</u>

The LightSwords foreground is limited to mastering of technology elements including its technology windows set up, i.e.

- The knowledge on the proper programming of micromachining to obtain required geometry of moulding tools including capability to obtain roughness regular for finishing processes – mostly shared between DAPP, CMS and ADV; the foreground remains proprietary of companies knowhow.
- The grey scale laser lithography exploitation for highly precise mechanical elements shaping; that foreground is still under promising progress and it remains proprietary of SKA, CMS and WUT.
- The conceptual set up for LSOE assessment procedure. That foreground remains the proprietary of SKA and CMS.

Gainika and SCAME gained foreground on limits of LSOE applicability in the protective goggles and in the surveillance cameras applications.

All partners of Consortium remains in the joint cooperation for successful exploitation of elaborated technology for commercialization including possible medical applications as contact lens and intraocular lens.

Conclusions:

<u>In general it may be concluded,</u> that the LSOE optical assessment proofed, that the lenses provide performance characteristics similar to the theoretical predictions. The two of investigated fabrication methods is ready for production start-up: hot embossing and injection moulding – both established on moulds manufactured with direct machining.

1. **direct micromachining may be used for requested surfaces of low curvature and it disclosed difficulties to obtain sharpness of step edges and in some cases sufficient surface smoothness.** Direct micromachining is also limited to complexity of the structure. Multi-zone structures may be very difficult or even impossible to manufacture with this method.
2. The injection moulding of lenses with micromachined **die provides optical structure manufacturing with very good repeatability.**
3. The **hot embossed lenses from directly machined stamp** give good optical performance. The surface transparency is excellent. LSOEs made with this approach seem to be the best of all samples produced during the project. **They provide good quality, easily recognizable images of the labels and Siemens Stars.**
4. **The grey scale laser lithography technology for moulds development still needs improvements.**
5. **The overall objective of LightSwords project was obtained; the capability to produce LightSwords structures was obtained with TRL 7.**