Development of cost-efficient micro-optics for headlight systems: Different loops of optimization leading to a glare-free and high range module

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ABSTRACT

We introduce the development process of a new headlight module with perfect colour mixing and sharp upper edge for use as an additional module. Light is nearly collimated (<0.5° cone angle) for a variety of high-power automotive LEDs illuminating up to 1000 m street in front of the car. Key to success is an optimization process not only of the optical elements but also the materials and parameters of the injection molding process. A feedback loop of geometry measurement and simulation of real geometries does lead to acceptable tolerance values and geometry deviations. Finally, the optics in the module needs to be optimized with respect to mechanical tolerances and the inevitable fabrication errors. In this case it resulted in an additional element to be added at the entrance and exit surface of the initially designed optical structure. All steps were accompanied or carried out by simulations with LucidShape and FRED.

1. INTRODUCTION

The design of optical systems is far more than the optical design itself. Most optical design software solutions offer some kind of sensitivity analysis tool to at least check the influence of some of the tolerances to the resulting image of the design. In most cases the thermal and structural analysis are decoupled from the optical system design process and results rarely find their way back to the optical designer. Unfortunately, this leads to a degraded performance of the first product/prototype. Although processes exist in different industries to co-work on the design and implement results of thermal and structural analysis into the optical design, they are not yet standard procedure. We want to show the benefit of directly implementing tolerance changes for different sources into the simulations of the optical design, including mechanics, to identify worst offenders in the system and adapt the optical design to be less sensitive with respect to those offenders.

2. MODULE IN TEST

As a showcase we choose a high-performance light module for automotive head lights. The primary design was for a high beam but with some modifications it can be used for other purposes as well. The SAE/ECE norm defines a strict radiant intensity pattern for the different types of head- and taillights. Originating from requirements in race sport the module is designed to illuminate a long strait street up to 1000 m distance without glare.

To satisfy these requirements a very small exitance cone is combined with the sharp upper bright-dark-border defined by the SAE/ECE norm. The collimating power of the standard (even freeform) collimators is not capable of creating these narrow cones. Our Nanolight packet redirects the light into the desired directions with the welcome side effect of perfectly mixing the colours of the emitted light.

Figure 1 shows the optical element arrangement of the module. The mechanical parts are not shown but need to be considered in all simulations to get reasonable results. Even the coating of some housing parts has non negligible effects on the light distribution.

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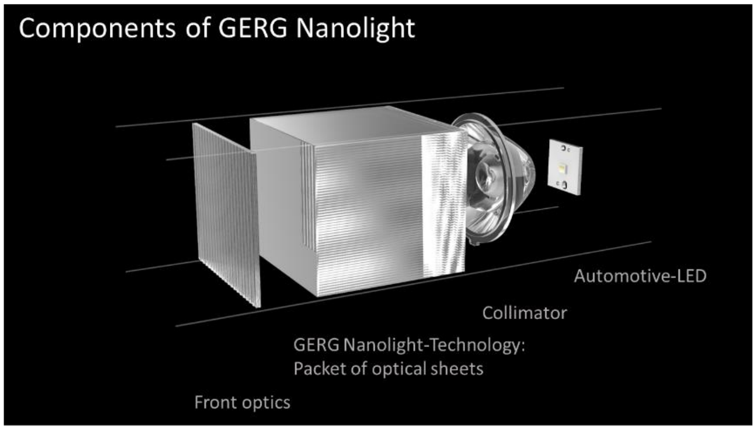


Figure 1. Components of the light module. A standard high power automotive LED, a collimator optimized to the profile of the LED, the GERG Nanolight packet and a front sheet.

The goal of the new module is to enhance visibility without glare or distracting shadows as known from classical head lights. Figure 2 shows the difference of light distribution on the street for three different systems. GERG NL does combine the benefits of standard high beam and matrix LED by illuminating a wide and far area of the street without glare on oncoming traffic and without shadows in the line of sight.

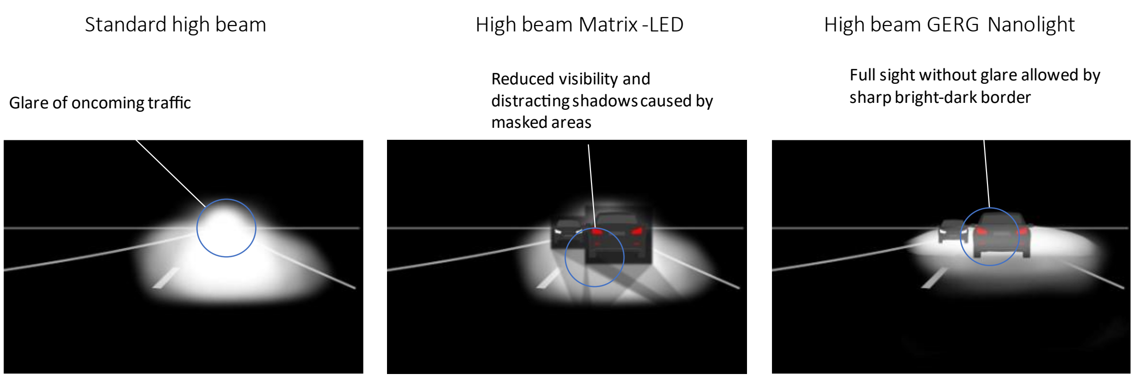


Figure 2. Comparison of standard high beam and matrix LED light with GERG Nanolight.

3. OPTIMIZATION STEPS

Figure 3 shows the flow chart of the optimization process.

The design needs to be optimized until the production output can be fully utilized within the tolerances (or at least to a high percentage) without failing the light distribution requirements. The steps include:

1. Measurement of mounting tolerances and sensitivity analysis (Chapter 4, red in flow chart)
2. Parameter Study to find an alternative design (Chapter 5, dark red in flow chart)
3. Building of prototype (grey in flow chart)
4. Measurement of quality/deviations of optical elements and sensitivity analysis (Chapter 6 and 7, orange in flow chart)
5. Modification of prototype (grey in flow chart)
6. Final design (Chapter 8, green in flow chart)

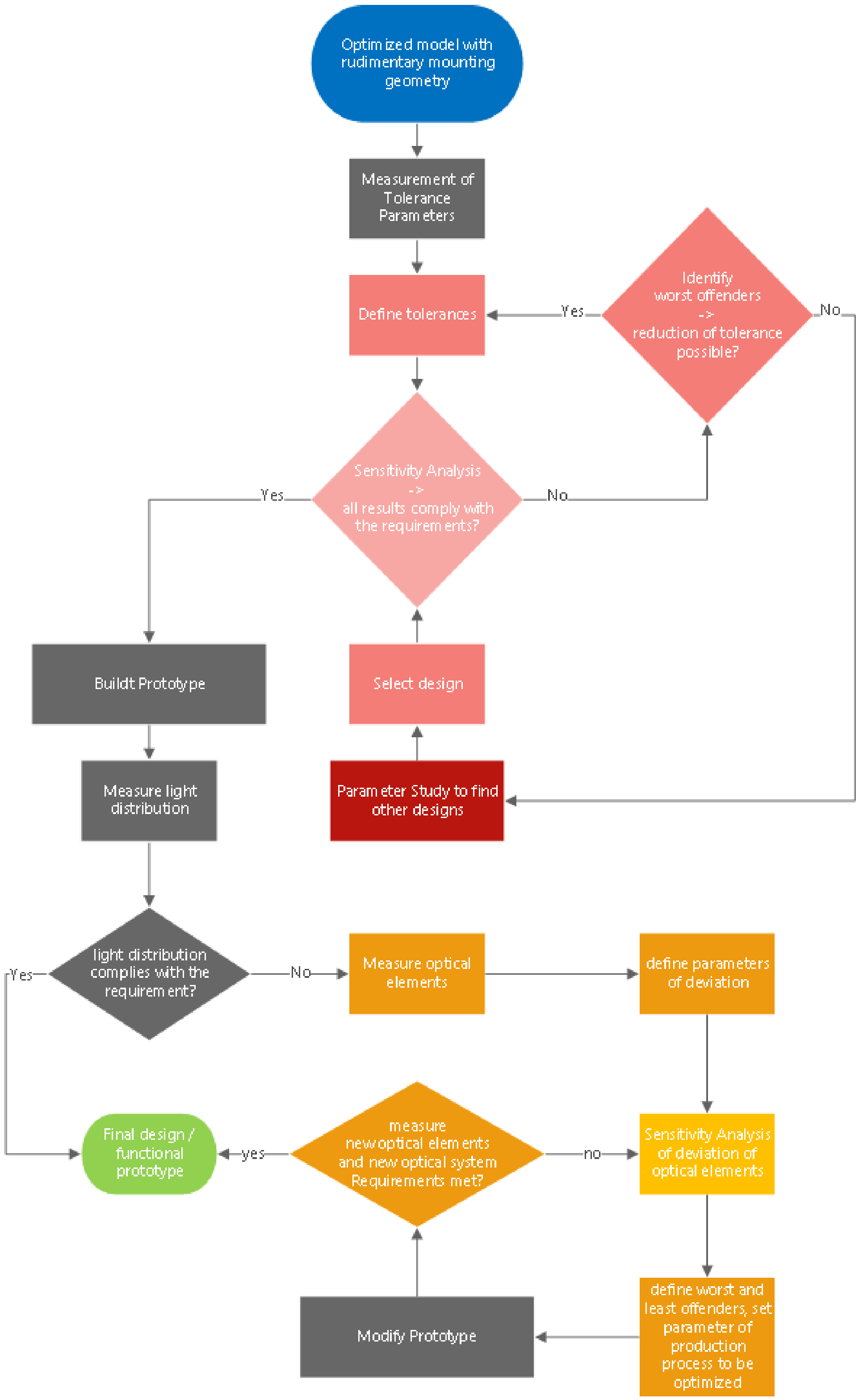


Figure 3. Flow chart of optimization process

For automotive light modules the ECE/SAE norm requirements are:

- Sharp bright/dark edge on the upper side
- An illuminance/radiant intensity matrix of additional sampling points

The resulting values of the requirement matrix after optimization for the high beam module are shown below:

Regulation: ECE R112 class A headlamp upper beam 13.2V

name	value [cd]	OK	min [cd]	max [cd]	test pos. [deg]	found pos. [deg]
Emax	212358	OK	27000	215000	0.10,-0.10	
HV>80%Emax	202925	OK	169887	--	0.00, 0.00	
H-5L	3606.6	OK	3400.0	--	-5.00, 0.00	
H-2.5L	22552	OK	13500	--	-2.50, 0.00	
H-2.5R	21866	OK	13500	--	2.50, 0.00	
H-5R	3491.5	OK	3400.0	--	5.00, 0.00	

The light distribution is OK

It doesn't come as a surprise that the first measured light distribution didn't comply with the simulated one. To identify the worst offenders, leading to the deviation, we measured the positioning and tilt of the LED surfaces and performed a sensitivity analysis based on the extracted tolerances. The simulation process did in addition consider variations of the collimator position and tilt.

4. SENSITIVITY ANALYSIS

The LED and collimator position and rotation were chosen as parameters for the sensitivity analysis. Deviations of those reflect the impact of mounting tolerances on the light distribution (Figure 4).

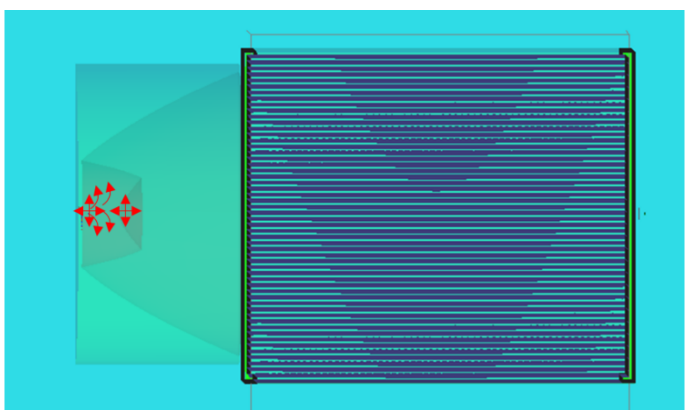


Figure 4. Simulation geometry for sensitivity analysis with 10 parameters composed of 3 positional LED parameters (x,y,z), 2 rotational LED parameters (rot-x, rot-y), 3 positional collimator parameters (x,y,z) and 2 rotational collimator parameters. Mechanical geometry is implemented as simplified surfaces. This setup requires $(3^3*3^2) * (3^3*3^2) = 3^{10} = 59049$ simulation runs.

For each parameter three values representative in a sensitivity analysis were simulated: nominal, max and minimum value.

Variation of the x-, y- and z-position of the LED leads to 27 (3^3) possible positions (see Figure 5). A rotation around the x- and y- axis will also change the direction of the incoming light to the sheets, while the rotation around the z-axis has no such effect. Therefore the 27 positional states have to be multiplied with 9 (3^2) additional possible angular rotations for the final number of 243 states of the LED placement. The number is identical for the collimator giving a total number of 59049 (243^2) cases that have to be considered and simulated in the sensitivity analysis.

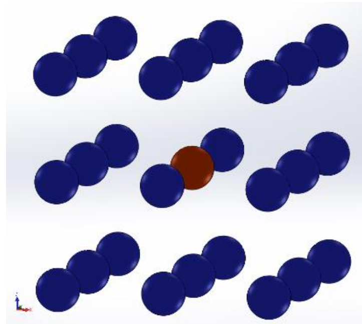
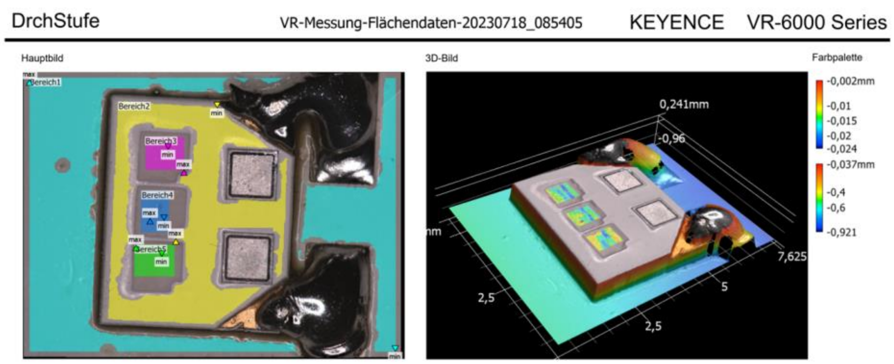


Figure 5. 27 (3^3) Possible positions as combinations of x-, y- and z-positions with nominal, max and minimum value each. The red sphere represents the nominal position.



	Höhenunterschied	Max. Höhe	Min. Höhe	Max.-Min.	Winkel zwischen Ebenen 1	Winkel zwischen Ebenen 2
	mm	mm	mm	mm	°	°
Summe	-0,717	-0,538	-0,970	0,433	896,552	3,448
Max.	0,000	0,029	-0,022	0,310	179,921	2,279
Min.	-0,673	-0,562	-0,872	0,019	177,721	0,079
Durchs.	-0,143	-0,108	-0,194	0,087	179,310	0,690
Std.Abw.	0,265	0,227	0,339	0,113	0,824	0,824
3 Sigma	0,794	0,682	1,017	0,338	2,472	2,472
Bereich1	-0,673	-0,562	-0,872	0,310	177,721	2,279
Bereich2	0,000	0,029	-0,028	0,057	179,921	0,079
Bereich3	-0,016	-0,005	-0,025	0,019	179,893	0,107
Bereich4	-0,015	0,005	-0,022	0,027	179,308	0,692
Bereich5	-0,013	-0,004	-0,023	0,020	179,710	0,290

Figure 6. Surface measurement of the mounted LED chip. In average the measured tolerance was higher than expected.

The max and minimum tolerance values used in the simulation were acquired by measurement as well as inferred from experience where direct measurement was not feasible.

The tolerances of LED and collimator position were estimated by experience. For the tip/tilt of the LED we decided to measure the glued LED chips, to get the tolerances of the combined module.

With a 3D Microscope several mounted LEDs were measured (Keyence VR-6000, see Figure 6). Due to the mounting strategy, it is not possible to improve their tolerances.

The simulated light distribution was tested against the ECE R112 class A headlamp upper beam 13.3V requirements and a simple pass/fail list was created.

The simulation showed that the setup is extremely sensitive regarding the tip/tilt tolerances, i.e. only parameter sets with the nominal values for tip/tilt fulfilled the requirement. The part of the list with “pass” was very short and thus forecasted a large percentage of rejected products in a series.

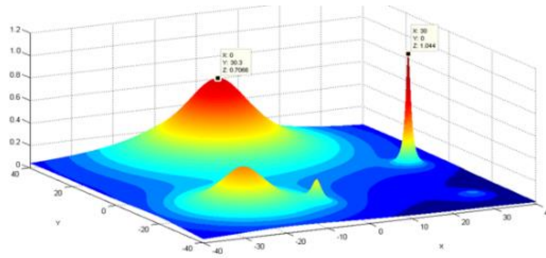


Figure 7. Exemplary example of an optimization result plane (arbitrary, here the merit function searches for a maximum instead of a minimum).

We had by chance obviously found an optimum in a very steep minimum (as the right peak in Figure 7). To be less sensitive or unsensitive to rotations of the LED we need to find a solution inside a flat minimum (as the two left peaks in Figure 7). No optimization of the current optical design would lead to stable light distributions for even a small production series. A new design needed to be found that doesn't show a high dependency of the LED and collimator position and rotation.

5. PARAMETER STUDY

A large parameter study on the geometry of the GERG Nanolight optical elements was performed to identify alternative designs that are less sensitive to the given tolerances. This study concentrated on the optical structure of the optical sheets.

The structure is similar to that of a blazed grating, just on another scale. Due to the size of the structure the light propagation can be treated purely geometric without taking diffraction into account. (see Figure 8). The size and angles of the structure define the exitance cone and total loss of the system. The initial design was extremely efficient but did implicate high demands for the pre-collimated light. Therefore, the goal of the parameter study was to find alternative designs with similar performance but less sensitivity. Figure 9 shows the parameters used for the simulation.

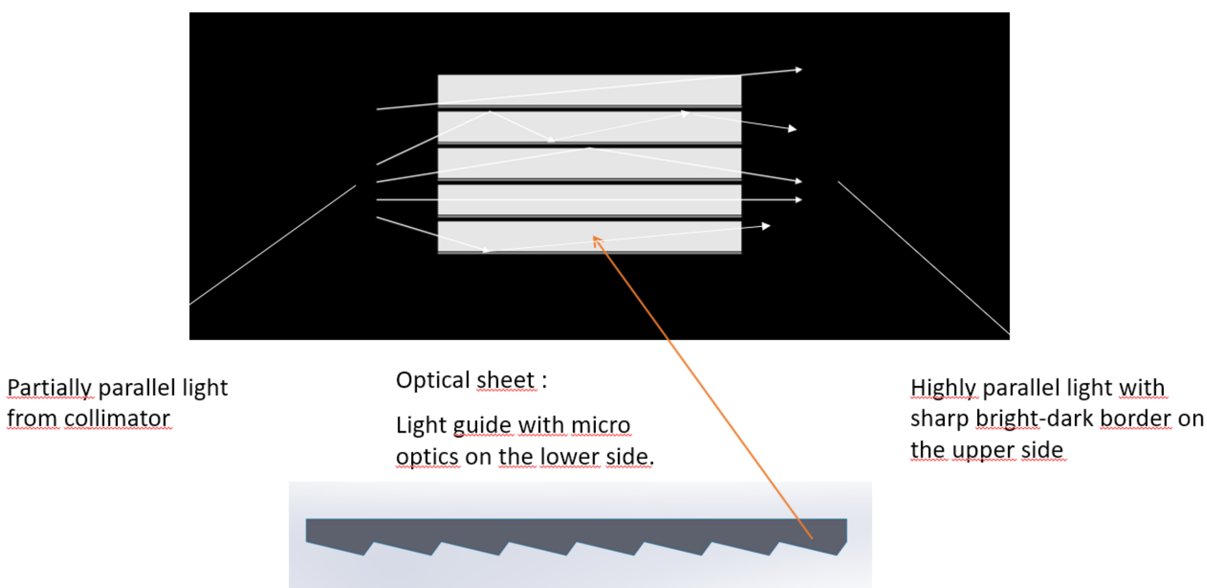


Figure 8. GERG Nanolight functional principle

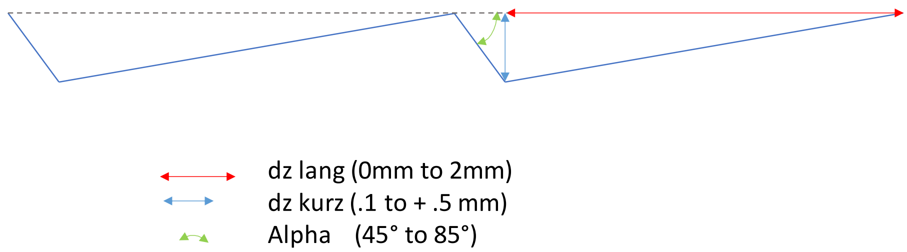


Figure 9. Parameter set for the parameter study; 20 steps used for each parameter.

For each parameter combination the following values were stored:

- the resulting light distribution
- the extracted radiant intensity values at the fixed angles defined in the SAE/ECE norm
- additional values to evaluate false light into the upper half of the distribution
- symmetry parameters

In total 8000 combinations with 10 result values and the related light distribution each.

Figure 10 shows a 3D visualization of the parameter space for E_{max}. It was created with an inhouse developed visualization tool (dviz) that allows to visualize multidimensional datasets as projections on 3D subspaces. A part of the parameter-combinations is geometrically impossible which is the reason that there are no datapoints below the diagonal plane in the figure.

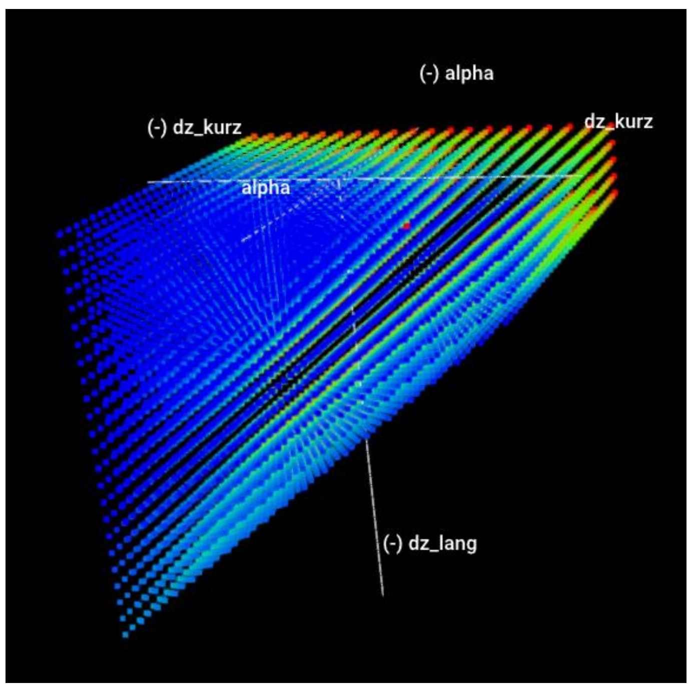


Figure 10. Colour coded visualization of E_{max} for the possible parameter combinations.

With dviz it is possible to interactively manipulate the 3-dimensional display (rotate, move, zoom) and investigate the colour encoded value of a selected 4th dimension, read out parameter- and result values for each datapoint and show the light distribution for selected points in a separate window. To reduce the clutter by datapoints that fail to satisfy a particular requirement it is possible to mask points below a threshold which can be individually defined per dimension.

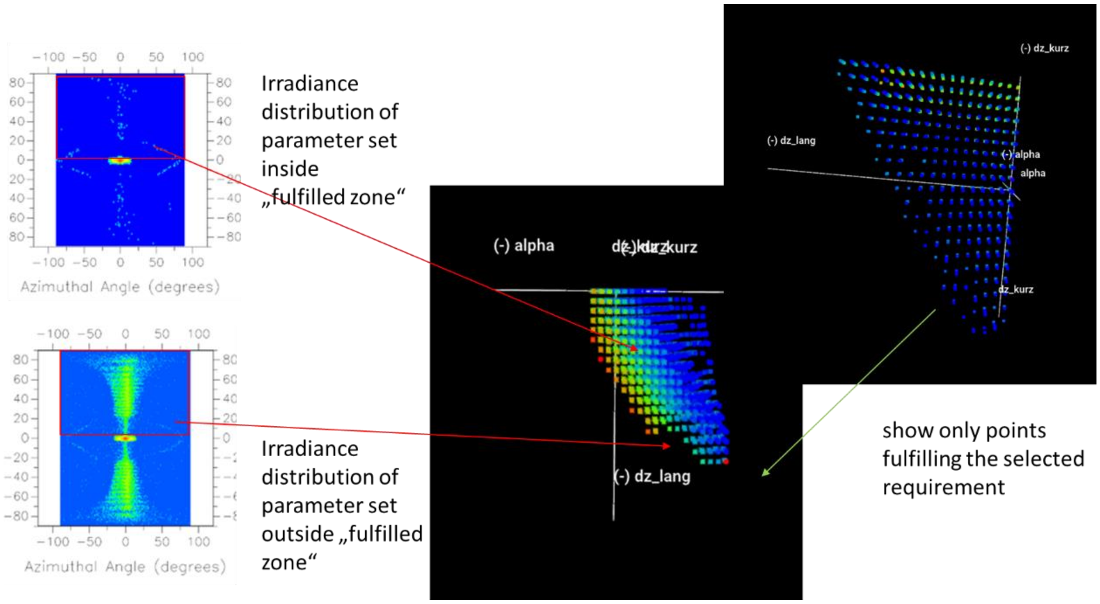


Figure 11. Colour code shows radiant intensity above the bright-dark border, upper right: full matrix, lower right: all parameter sets with less than 1 Lux above the border.

dviz also allows to extract 2D cross sections of the displayed data and visualize the currently colour encoded dimension as the third spacial dimension. The colour encoding in the cross section display can then be used to visualize another dimension, which enables the visual correlation of different parameters.

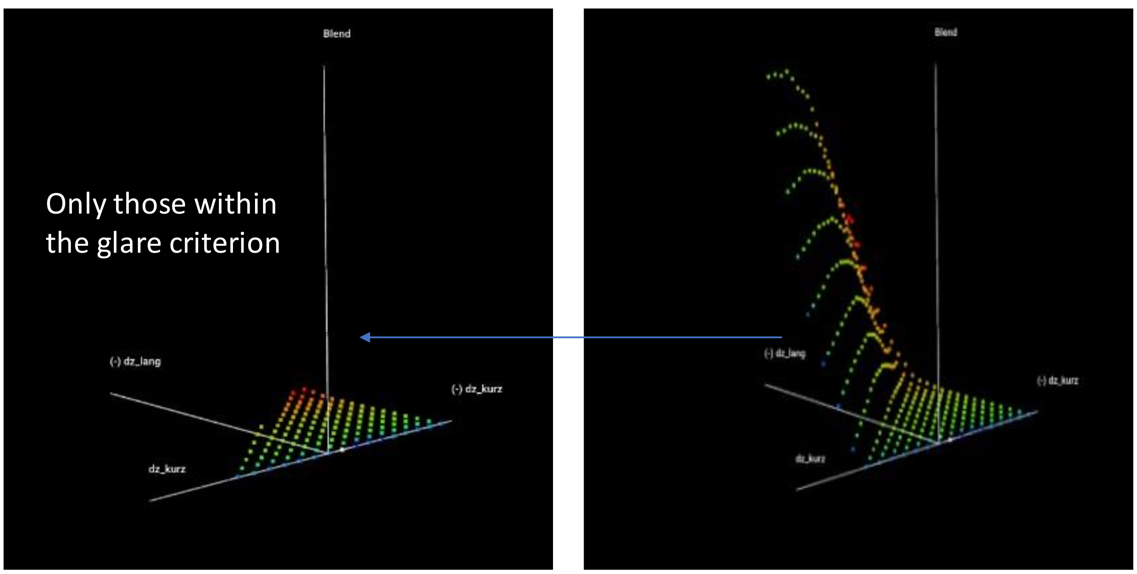


Figure 12. Extracted plane (from Figure 11), glare shown as z-value, colour code is set to HV value.
Left side: points compliant with the glare requirement showing a more or less flat plane.

The tool was used to identify regions where the points build a flat plane with respect to the requirement values. The expectation is that those are in general less sensitive for deviations. Figure 12 shows one of those parameter regions for the glare requirement.

Form the identified candidate regions, the ones best suited for injection molding were chosen and new optical sheets were produced.

However, the resulting light distribution still didn't match the simulated one.

6. ANALYSIS OF OPTICAL SHEET

Until that point simulations were carried out with ideal geometries. No errors of any kind (except tolerances in shift and rotation) had been taken into account. Visual inspection of the optical sheets showed defects in the surfaces that implied a not fully optimal injection molding process. 3D microscopy was not suitable to inspect the transmissive surfaces of the sheet, therefore they were analysed by a laser-scan-microscope (Keyence VK-X3000).

The first batch of new optical sheets didn't show the desired contours. The material hadn't fully filled the tool and thus built out different angles and large radii instead of edges. Also defects in the optical surface can be seen (Figure 13). Both artefacts create unwanted false light in the system.

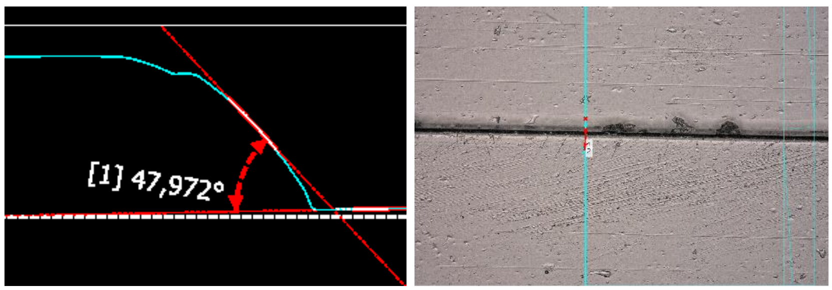


Figure 13. Measured contour of first batch optical sheet microstructure. On the right side the surface of one of the structures is shown.

Based on these findings the injection molding process was optimized. Unfortunately, higher temperatures that enabled a good filling of the tool also resulted in distortion of the sheet. A compromise between flatness of the sheet and exactness of the contour had to be found. To define, which parameter requires the lower tolerances, simulations with different radii and distortions of the flat surface were carried out (see chapter 7). With the results of those simulations the injection molding process was optimized until satisfactory results were achieved (Figure 14).

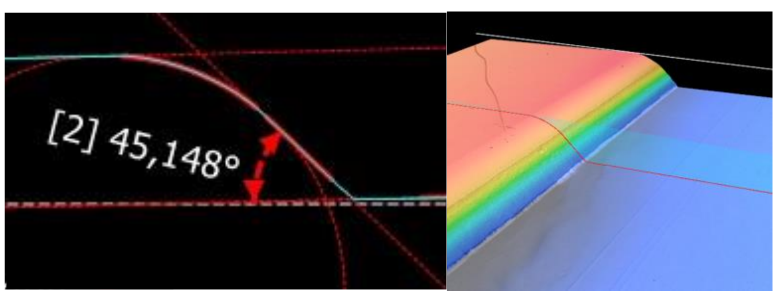


Figure 14. Measured contour of optical sheet microstructure final batch.

7. SIMULATION OF SHAPE DIFFERENCES

The influence of shape deviations of the optical sheet was simulated with ideal positions of the collimator and LED. The assembly was modeled as a parametric system in FRED allowing to change angle, height and radii via input or loop parameters. The first simulation was performed with input values obtained by the analysis described in chapter 6 to compare it with the measured light distributions. Figure 15 shows some examples of simulated geometries and resulting light distributions. The angle deviation had an impact on the amount of false light above and below the nominal pattern, the radii to the width of the false light pattern.

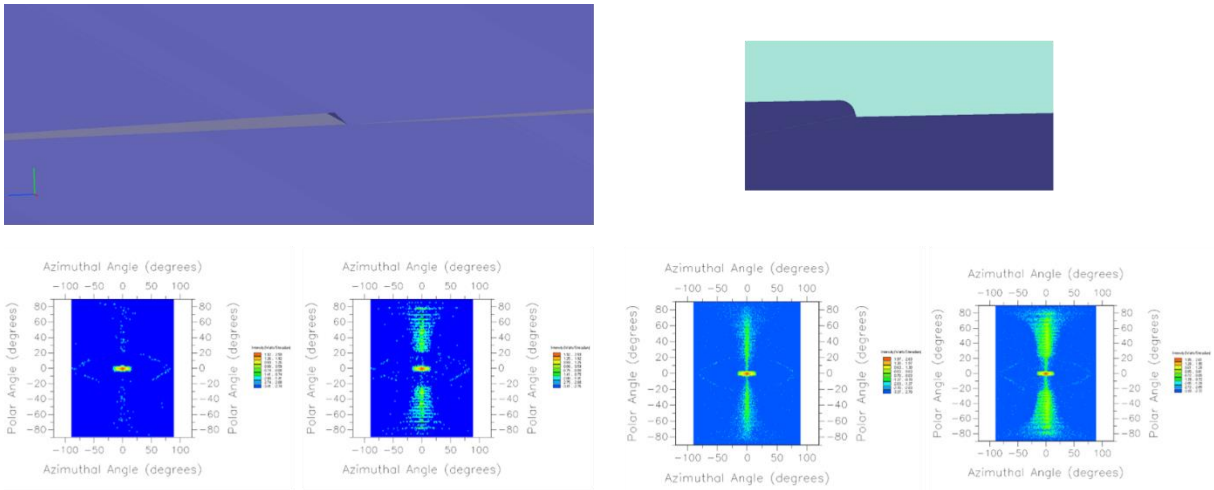


Figure 15. Examples of simulated structure and resulting light distributions.

With the confirmation that the deviations in light distribution were correlated to the geometry deviations, a sensitivity analysis was carried out to show which of the deviations has the least impact and thus doesn't need to be that well-adjusted. Contrary to expectation the waviness of the optical surfaces had less impact than the angle and radius of the structure. This allowed to use a higher temperature for the injection molding process.

8. FIRST PROTOTYPE

With these optimized optical sheets and parameters for LED and collimator a prototype was built with housing etc (Figure 16). The first light with this prototype was disappointing. We must have missed another offender and the light distribution still didn't match the simulated one.

The first idea was that there might be gaps in between the sheets, leading light on unpredicted paths through the system.

- We tested with pressure on the sheets to reduce possible gaps, which had no effect.

The second candidate was the side surfaces of the sheets that served as in- and outcoupling surface.

- We tested with polished side surfaces, which showed no improvement as well.

Finaly, the solution was to glue an additional plate onto the two side surfaces with an optical index matched glue. The outfacing surfaces are polished plane and ensure perfect in- and outcoupling. The index matched glue fills every possible gap in between the innerfacing surface and the uneven surface built by the multiple side surfaces of the sheets.

The additional optical element also allows to use the module in multiple applications since the outcoupling plate can be built as an optical active element and shape the light distribution in addition to the GERG Nanolight package.

Further development is focused on optimising the side surfaces of the plates to reduce the glueing effort to only one exit surface.

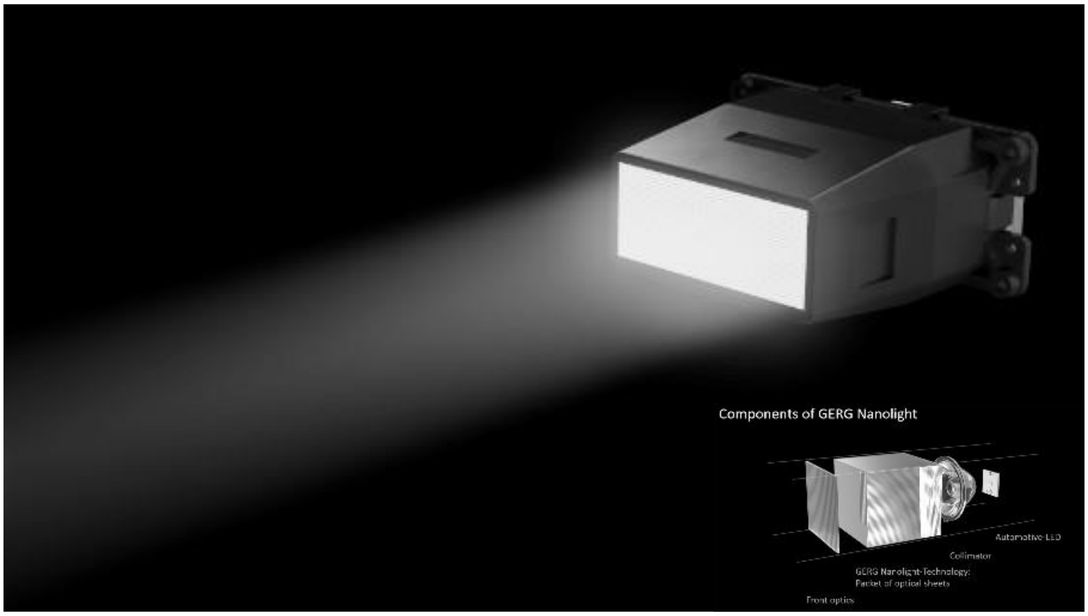


Figure 16. Prototype of GERG Nanolight module.

The next figures show the GERG Nanolight as high beam and as custom road illumination module (Figure 17) and illuminating a street (Figure 18 and Figure 19).

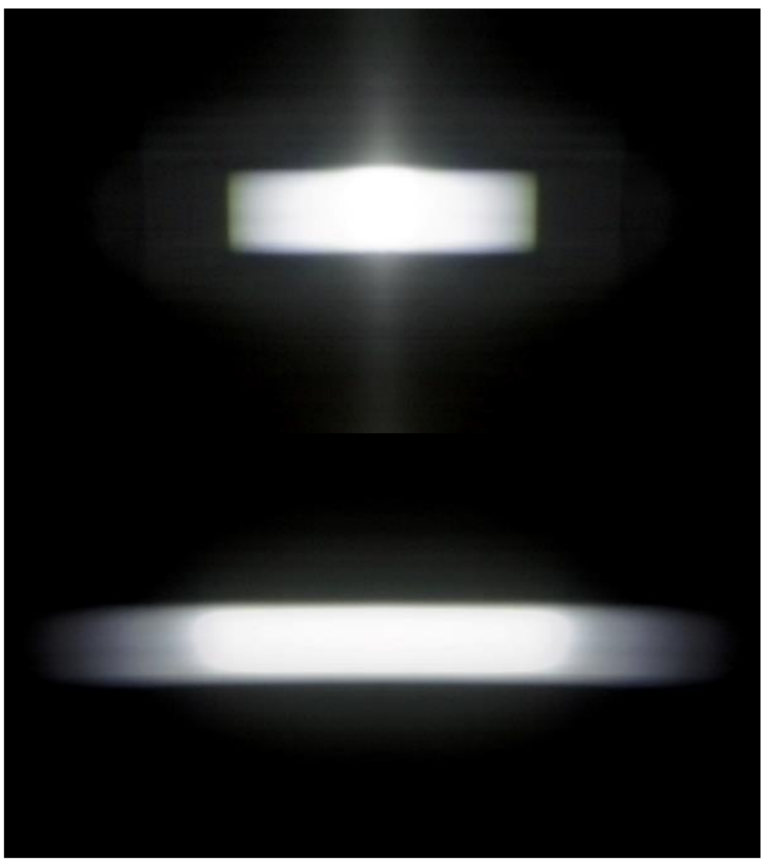


Figure 17. GERG Nanolight as high beam (upper) and custom road illumination (lower).

Figure 18. Street illuminated by GERG Nanolight custom road illumination module. Near area and sides are homogeneously illuminated.

Figure 19. Street illuminated by GERG Nanolight high beam module. The area beside the cars is now fully illuminated (dark in Figure 18). Driver seat is only slightly illuminated.

9. CONCLUSION

The optical design process of a light system is not finished with the first optimized design. Production tolerances, mounting deviations and thermal effects can have a large impact on the real world performance and need to be taken into account.

Simulations can help to find the worst offenders. Exact measurements are necessary to define realistic tolerance ranges. The limits of tolerance minimization determined by the production technology have to be identified.

Parameter studies can help to find better designs with respect to sensitivity. For mass production a less sensitive design will have less wastage and thus less cost.

The process described in this paper only works in well collaborating teams. A fast and intensive exchange of information is mandatory.

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