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Research Article

Dennis Zimmermann*, Andreas Beutler, Matthias Brozio, Simon Freutel, Philipp Kosse and Cornelius Neumann

A procedure for designing and manufacturing microstructured lenses used in automotive headlamps

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Abstract: The transition between the light and dark areas of the luminous intensity distribution of a headlamp needs to fulfil statutory regulations. For projection headlamps, adjusting the transition is done by adding a scattering structure to the lens surface. The requirements for the transition are pointed out, and typical problems are presented. A procedure to create such scattering structures in computer-aided design is shown. Improvements to the controls of turning machines for manufacturing are discussed. A reverse engineering process using a high-precision cylindrical coordinate measuring instrument with an optical probe for quality assurance is presented.

Keywords: diamond machining; headlamps; metrology; microstructures; reverse engineering.

1 Introduction

When creating automotive headlamps, the time-to-market period becomes ever shorter. Often, the first manufactured parts are already delivered to the customer and therefore must have the quality of a series product. On the one hand, the headlamp has to match the customer requirements; on the other hand, it has to fulfill statutory regulations such as the Economic Commission for Europe (ECE) or the Federal Motor Vehicle Safety Standards [1, 2].

These regulations define, among other things, the mandatory behavior of the transition between the light and dark areas of the light distribution, the so-called cutoff line. The gradient of the cutoff line has to be in a specific range. For a projection headlamp as shown in Figure 1, the shaping of the gradient is done by adding a light scattering structure to the light exit surface of the lens. As the amplitude of the structure is in the range of some micrometers, the term microstructure is used. The scattered light makes the cutoff line smoother, resulting in a gradient which complies with legal requirements (see Figure 2). It is challenging to design and manufacture lenses with enough scattering that produces a soft, but still distinct, cutoff line but that do not exceed glare limitations.

Creating a stable and fully controllable process for designing and manufacturing microstructured plastic lenses produced by injection moulding was the goal of the funded project *ePiTec* [3]. This paper presents the results of the project. An overview of the complete process is given in Figure 3. To achieve the microstructure on the light exit surface of the lens, the structure has to be added to the mould inserts. Our approach to design such structures is described. Improvements to the controls of turning machines are pointed out. As in every other manufacturing process, deviations may occur. To check if the manufactured surface still fulfills the requirements, an optical measurement of the mould inserts and a surface fitting are performed. The resulting surface is used in a ray-tracing simulation to qualify the mould inserts. The measurement system and the fitting procedure are described, and the first results are presented.

2 Requirements and typical problems

The gradient G of a luminous intensity distribution of a headlamp is defined by [1]

***Corresponding author: Dennis Zimmermann,** HELLA GmbH & Co. KGaA, Lippstadt, Germany, e-mail: dennis.zimmermann@hella.com. https://orcid.org/0000-0003-4043-9192
Andreas Beutler: Mahr GmbH, Göttingen, Germany
Matthias Brozio, Simon Freutel and Philipp Kosse: Innolite GmbH, Aachen, Germany
Cornelius Neumann: Lichttechnisches Institut, Karlsruher Institut für Technologie, Karlsruhe, Germany

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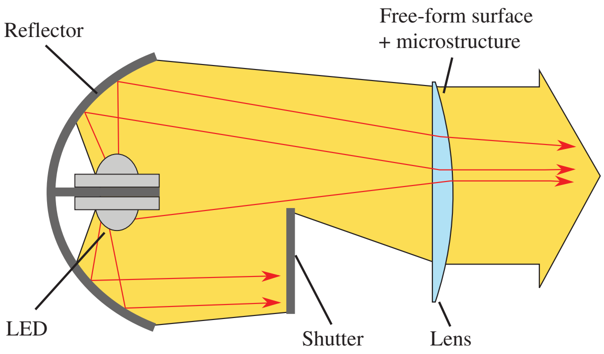

Figure 1: Schematic drawing of a projection headlamp.

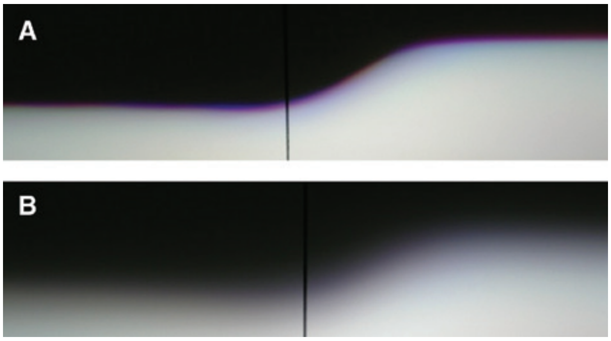

Figure 2: Light distributions of headlamps on a wall. (A) Lens without microstructure. (B) Lens with microstructure.

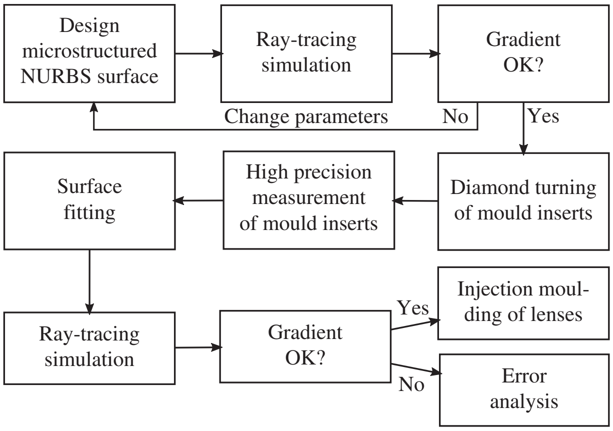

Figure 3: Flowchart of the complete process from design to injection moulding of microstructured lenses.

$$G(\beta)=\log(E(\beta))-\log(E(\beta+0.1^{\circ})) \tag{1}$$

where E represents the luminous intensity at a vertical angle β. By ECE regulations, the curve given by (1) is evaluated at a horizontal angle of –2.5° and has to have a single maximum with a value between 0.13 and 0.4. The position of the maximum value of the curve defines the position of the cutoff line. In Figure 4, different gradients are shown. A headlamp with an unstructured lens generates a cutoff line (blue line) that is too hard. By adding a well-functioning microstructure to the lens, a smooth cutoff line in compliance with law is obtained (green line). If inaccuracies in the design or manufacturing process of the mould inserts occur, the gradient may take unwanted shapes, such as having multiple maxima (orange curve) or falling off at high angles (red curve). Since the maximum of the gradient is used for alignment, multiple maxima may lead to misaligned headlamps that do not comply with legal requirements. A gradient falling off at high angles is accompanied by a lot of scattering light that dazzles oncoming traffic.

3 Designing microstructured lenses

The optical surfaces of headlamps are designed using computer-aided design and simulated with ray-tracing software. In both systems, surfaces are described with non-uniform rational basis spline (NURBS) [4]. Therefore, the result of the microstructure design process has to be a NURBS surface. The steps to add a microstructure to a lens are shown in Figure 5. The dashed red line represents the surface of the unstructured lens. The lens surface is rasterized so that a point grid is generated, which is equally spaced in the plane orthogonal to the optical axis of the lens (black dots). At each raster point, the normal vectors of the surface are calculated (black arrows). A point grid (cyan dots) representing the structured surface is generated by adding specific offsets along the normal vectors to each raster point (black dots). The microstructured surface (cyan line) is obtained by calculating an interpolating cubic NURBS surface of the grid [4].

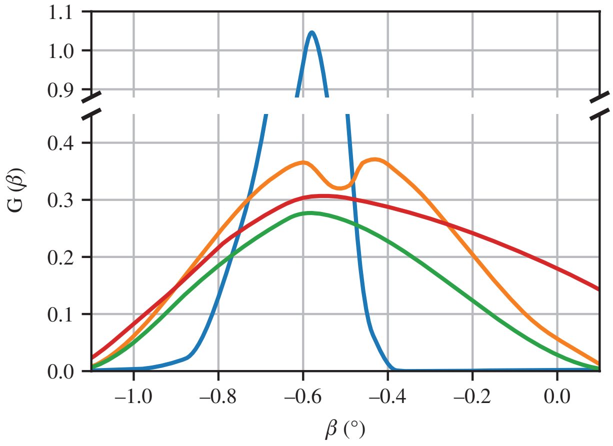

Figure 4: Examples of typical gradients of cutoff lines.

The surface is used in a ray-tracing simulation to determine the luminous intensity distribution formed by the surface. The gradient of the distribution is analyzed. If the gradient does not match the requirements, the parameters of the microstructure, either the grid spacing or the offsets, are modified until the desired gradient is achieved.

Initially, periodic structures as shown in Figure 6 were used to smooth the cutoff line. It is challenging to design a sinusoidal structure not causing a gradient with two maxima (see orange curve in Figure 4). Even if a periodic structure is successfully designed, small production deviations can lead to a gradient with two maxima. By using microstructures based on stochastic distributions, the risk of getting more than one maximum is reduced.

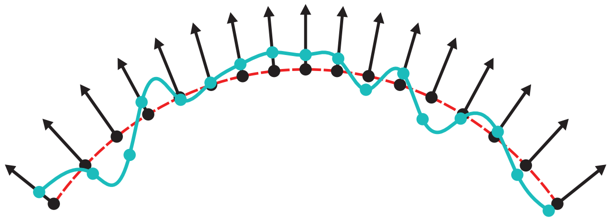

Figure 5: One-dimensional illustration of structuring a plane surface.

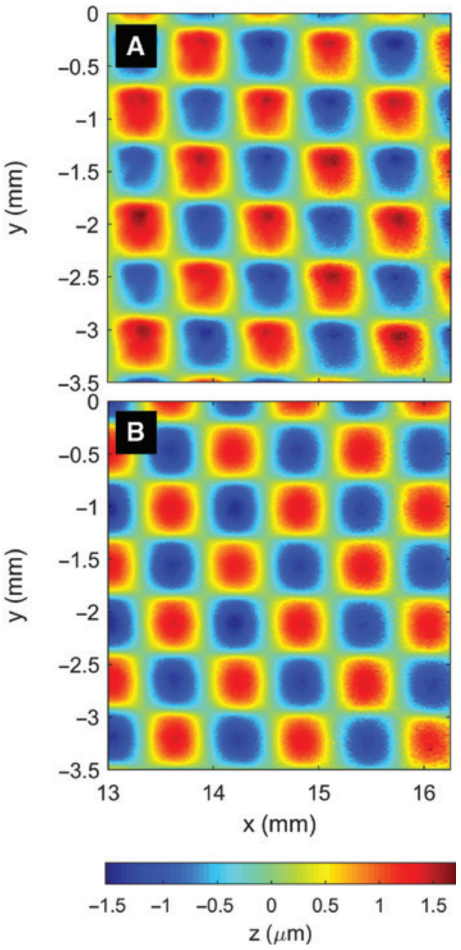

Figure 6: Sinusodial microstructures manufactured and measured using confocal microscopes. (A) Using conventional CNC. (B) Using DirectDrive.

4 Manufacturing of mould inserts

As described above, the well-defined regulations regarding the gradient of the cutoff line set high demands for the superimposed microstructure and, hence, for the manufacturing process of the mould inserts. Therefore, diamond turning is used for manufacturing [5]. Achieving a high surface quality requires highly accurate raw data quality at high resolutions. A common mould insert for LED headlamps including microstructures with a diameter of 70 mm is typically described by approximately 50 million datapoints. These datapoints have to be converted into a machine path (spiral) that consists of a subsequent list of set points which are processed by the ultraprecision turning machine. The conventional computerized numerical control (CNC) system of the machine adds the temporal information to the geometrical data (set points) and calculates the resulting control inputs for all axes in real time while taking account of dynamic restrictions such as speed, acceleration and jerk. CNC systems also provide a so-called look-ahead functionality, which is the processing of set points that are not yet reached by the physical axis. This is to provide the ability to fully stop all movements of the machine in case possible errors in the geometrical path are detected at all times.

A high density of set points combined with the look-ahead functionality of the CNC kernel always results in a severe limitation of production time. Another issue is the geometric accuracy of the manufactured surface. The CNC kernel calculates all control inputs with respect to the predefined maximum dynamic limits of the axes. This behavior can lead to excessive subsequent errors in specific areas, which strongly affect the resulting geometry.

Finding a feasible combination of the set point density and the maximum axis feed rate and, hence, the production time is a complex task for conventional CNC machine operators. The disadvantage of the conventional real-time approach is that it detects any exceeding of the dynamic axis limits only during machining, which may require multiple iterations of machining the same part until there are no errors stopping the machine. The resulting surface quality can only be validated measuring the final part. Otherwise, it is unknown if, e.g. the set points were sufficiently dense for machining the specific microstructure.

Therefore, for the project of this paper, we used DirectDrive3D by Innolite GmbH, a completely new control system that overcomes the above-mentioned restrictions of the conventional CNC and allows for an unlimited set point density without any restrictions in terms of production time or process speed, respectively [6]. By providing constant streams of fully interpolated and synchronized control inputs directly to the servo drives of all axes, DirectDrive3D circumvents the need for a CNC control (G-Code) and, therefore, any look-ahead functionality. Since the mathematical calculation of all control inputs is done prior to the manufacturing process, it provides absolute control over the complete toolpath and also allows for selective adjustments of the cutting speed in order to prevent any defects on the resulting surface caused by excessive subsequent errors.

Figure 6 shows a microstructure manufactured by a conventional CNC system compared to the same microstructure manufactured by DirectDrive3D. The shape of the microstructure is significantly more precise with DirectDrive3D. A significant improvement of the optical result was achieved, i.e. of the slope error and the geometric accuracy.

5 Optical measurement of mould inserts

For the measurements of the mould inserts, the measuring system MFU200 was applied [7]. The system is a so-called formtester. It is a high-accuracy cylindrical coordinate measuring machine based on two linear measuring axes and one rotational measuring axis (Figure 7). The mechanical setup is very stable, consisting of high-precision axes and an internal compensation system which consists of a set of capacitive sensors measuring distance changes to a reference frame. The signals from the capacitive sensors are used to correct the measurement values for any nonsystematic movements of the axes, e.g. because of load changes or a nonrecurrent behavior of the guidings. In addition to the three measuring axes x, z and c, the system contains additional axes for positioning: a y axis for searching for the zenith, a rotational axis for rotating the probe system in between measurements and four axes inside the table on the c axis for centring and tilting.

The system can be equipped with both a tactile and a new type of optical point sensor. This creates an additional amount of flexibility, as the tactile and optical sensors have different advantages and limitations [8]. For this application, an optical probe sensor setup based on white light interferometry was developed. The goal was to obtain a high-resolution sensor with real-time data processing for tracking processes, i.e. by receiving the height values from the probe, the system can follow the contour of the sample in real time. In addition, the probe system has a small, lightweight and exchangeable probe, i.e. a small optical system with a fiber connection. The system is capable of measuring not only rotational symmetric aspheric lenses but also non-rotational symmetric samples such as toroids [9]. Figure 7 shows the system equipped with the clamping device and the mould insert. In order to determine orientation of the mould insert, the system can measure the edges with the tactile probe. The position of the optical relevant surface is determined with a set of lines or circles collected with the optical probe (see Figure 8). The samples were measured with a few hundreds up to 1300 circles. An example of a measuring result of a mould is presented in Figure 9. The figure shows the differential topography after subtracting the aspherical shape. Clearly seen is the structured surface with structure heights up to 3 μm. This is the first time that a structured surface, such as this one, could be measured completely, thereby describing the overall shape and the fine structure. In the past, only small sections could be measured with white light interferometers or confocal microscopes.

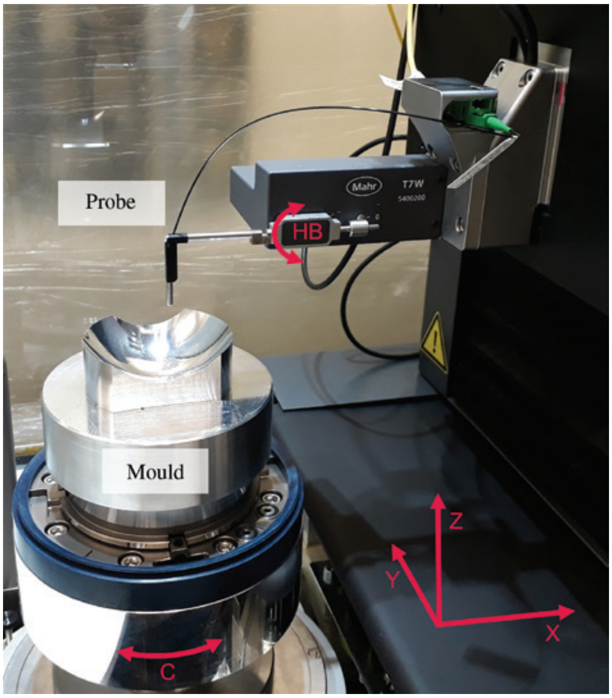

Figure 7: Mould insert placed on the measurement device.

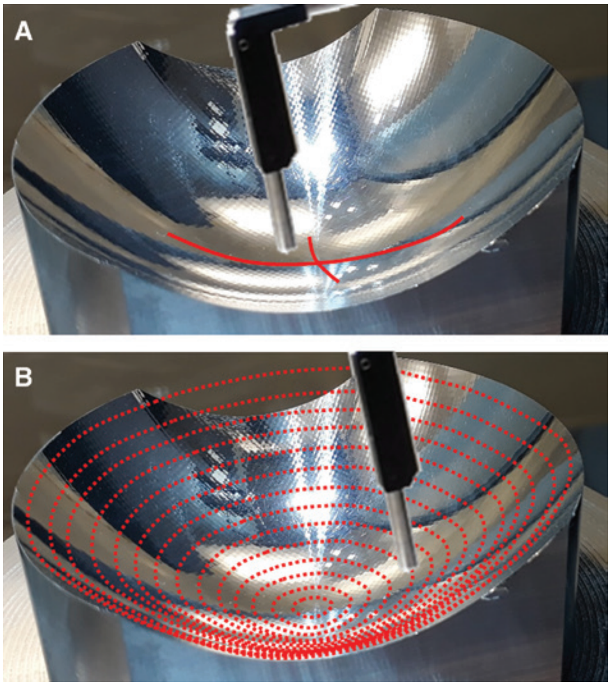

Figure 8: Movements of the probe for adjustment (A) and measurement (B).

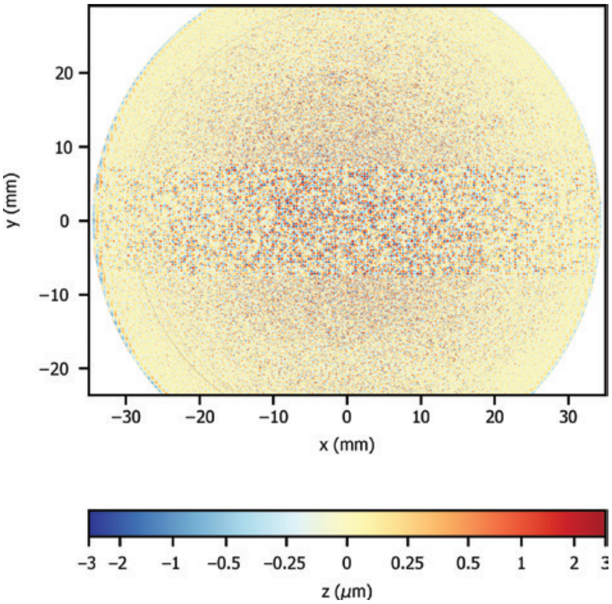

Figure 9: A measurement of a complete mould insert containing a stochastic microstructure. The map shows the differential topography after subtracting the aspherical shape. The color scaling is below −0.5 μm and above 0.5 μm logarithmic.

The horizontal band in the structure, as shown in the profile map in Figure 9, is part of the design. The headlamp setup used here has the property wherein the low beam and high beam light pass through the same lens. Most of the low beam light passes through the center part of the lens. To get the target gradient without disturbing the high beam light too much, it is necessary to scatter more light in the center part.

6 Reverse engineering

Because of possible deviations between the manufactured mould insert and the design geometry, the mould insert has to be qualified. Since the photometric result has to match the requirements, it is not appropriate to specify geometrical constraints for the surface of the mould insert. Instead, the mould insert is measured with MFU to obtain a point grid. A ray-tracing simulation directly based on the point grid is not suitable, because information of the surface between the points is needed. Therefore, a surface representing the point grid has to be calculated. In contrast to the design process (see Section 3), interpolating the point grid is not wise, because interpolation would bring the measurement noise into the surface. To fit a surface, the geometric approximation algorithm in combination with the second-order orthogonal projection method is used [10, 11].

The geometric approximation algorithm requires a starting surface for the fitting procedure, which is calculated by interpolating the point grid of the unstructured lens (black dots in Figure 5). The starting surface has the same shape as the nominal lens surface but the same number of control points as the structured lens surface. The algorithm reduces the deviation between the surface and the data of the optical measurement iteratively. The iteration is stopped when the change of the mean deviation between two steps is less than 1 nm.

7 First tests

As described in Section 3, a microstructure was added to an aspheric lens with a diameter of 70 mm. A grid spacing of 100 μm was used. The offsets were drawn from a normal distribution to generate a stochastic structure as shown in Figures 9 and 10. A file containing 50.4 million points describing the structured surface was generated (see Section 4). A mould insert was manufactured and measured as presented in Sections 4 and 5. A surface was fitted and simulated following Section 6. In Figure 11, the resulting gradients are shown.

The luminous intensity distribution of the designed surface has a slightly lower gradient than the fitted surface of the measurement and the measured light distributions of three lenses. The slightly harder gradient of

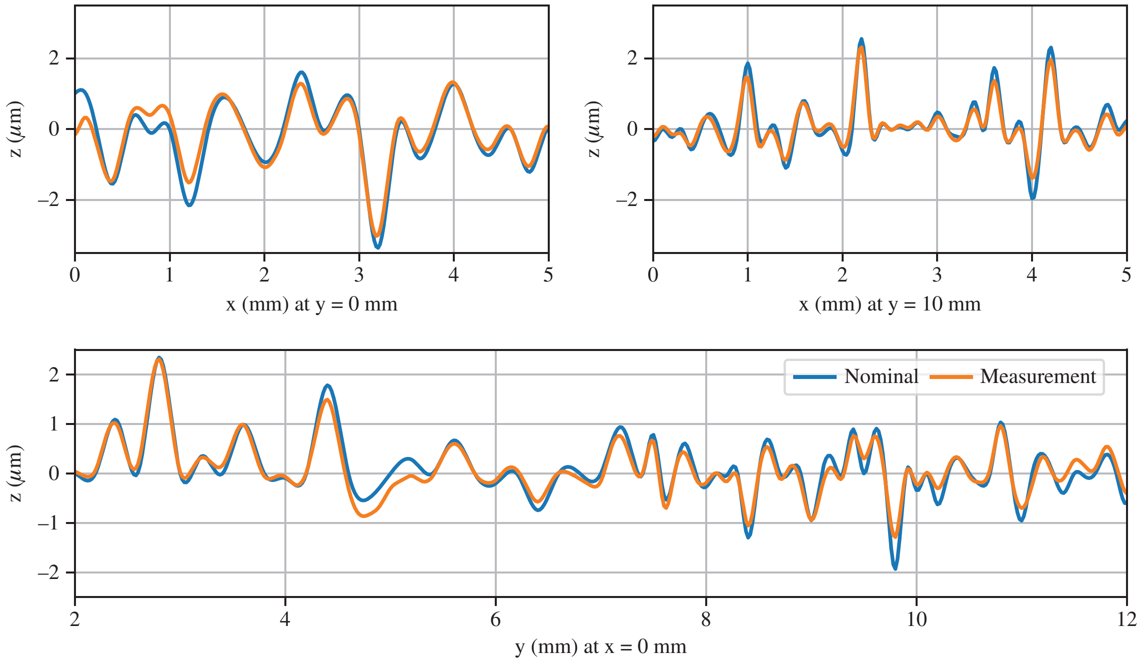

Figure 10: A microstructure designed with the procedure described in Section 3 (blue line) and a mould insert measured as explained in Section 5 (orange line). The aspheric surface of the lens was removed by fitting to show only the structure. The *x* and *y* coordinates refer to Figure 9.

the reverse-engineered surface is based on small deviations between the nominal surface and the manufactured surface (see Figure 10). The amplitude of structure in the mould insert is slightly lower than designed, as can be seen by a direct comparison between manufacturing and measurement data. The lower amplitude results in lower light scattering and in a harder gradient.

As explained in Section 2, the maximum of the gradient should be lower than 0.4, which was not achieved. This is due to the fact that the lens was produced without overhead sign functionality. By ECE regulations, a specific amount of light needs to be directed upward to illuminate overhead signs [12]. This is done by modifying the light entry side of the lens. The upward directed light affects the cutoff line. In order to see only the effect of the microstructure, the overhead sign functionality is omitted here. Simulations have shown that if the lens entry side had contained the overhead sign functionality, the gradients shown in Figure 11 would have been 0.03 lower and, therefore, would have complied with legal requirements.

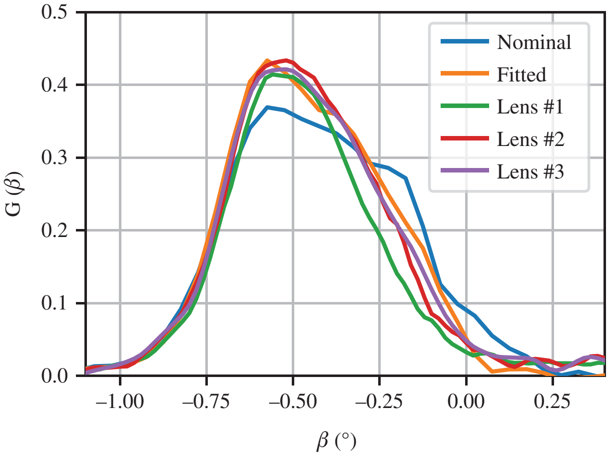

Figure 11: Resulting gradients. Blue: simulation of the original surface. Orange: simulation of the fitted surface. Green, red and magenta: measured luminous intensity distributions.

8 Conclusions and outlook

Our approach to design microstructured lenses in combination with improvements to the manufacturing process using diamond turning leads to the desired results. As shown in Section 7, the designed gradient was reproduced by the manufactured lenses except for some small differences. These small deviations could be explained using the reverse engineering process described in Sections 5 and 6.

To prove that the proposed procedure is reproducible, further tests with different microstructures and lenses have to be performed. The design procedure given in Section 3 is highly experience based and uses a trial-and-error loop to determine the parameters of the microstructure. We are currently investigating optimization algorithms to automate the design of microstructured lenses.

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Dennis Zimmermann
HELLA GmbH & Co. KGaA, Lippstadt, Germany, e-mail: dennis.zimmermann@hella.com. https://orcid.org/0000-0003-4043-9192

Dennis Zimmermann studied Physics at TU Dortmund University and wrote his master thesis on accelerator physics at the Zentrum für Synchrotronstrahlung. Since 2016 he has been working as doctoral student at HELLA GmbH & Co. KGaA, Lippstadt, Germany. His research focuses on the calculation of optical surfaces, light technical simulation and quality assurance of automotive plastic lenses.

Andreas Beutler
Mahr GmbH, Göttingen, Germany

Andreas Beutler studied Physics at the Universities of Bremen and Hamburg, Germany. He wrote his doctoral thesis on Surface Physics at Lunds University/MAXlab, Sweden. Since 1999, he has developed measuring instruments and performs research at Mahr GmbH, Göttingen, Germany. He is responsible for advanced technology developments and research projects. His emphasis is on profilometry, optical sensors, and metrology for optics production.

Simon Freutel
Innolite GmbH, Aachen, Germany

Simon Freutel studied Physics at the University of Duisburg-Essen and wrote his diploma thesis on plasma physics at the Forschungszentrum Jülich. Afterwards he moved back to the University Duisburg-Essen and wrote his doctoral thesis on solid state physics. Since 2011 he been working in the field of optics for Innolite GmbH in Aachen. He is responsible for the software development department at Innolite and develops new control systems for ultraprecision turning machines.