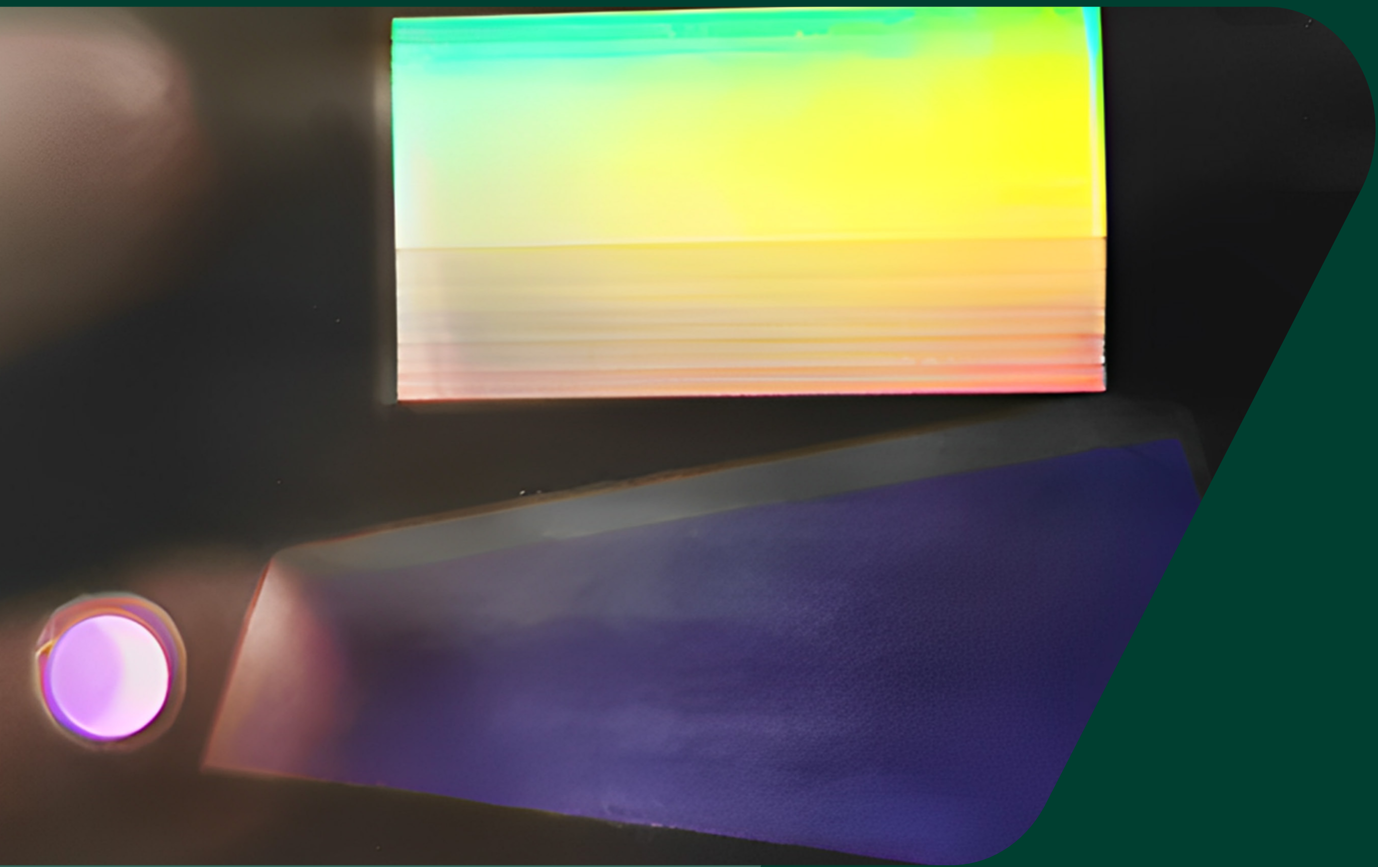
Growing Innovation

SUSS

Whitepaper

Optimizing manufacturing of augmented reality waveguides by combination of precision inkjetting and nanoimprinting



Dr. Fabian Kloiber, Dr. Simon Drieschner, Dr. David Volk, Dr. Marc Hennemeyer
SUSS MicroTec Solutions, Schleissheimer Str. 90, 85748 Garching, Germany

Dr. Mikko Poutanen, Dr. Jarkko Heikkinen, Dr. Pekka Katila, Tia Wilen-Gört
Inkron Oy, Olarinluoma 9, 02200 Espoo, Finland

INKRON

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Abstract

Augmented Reality (AR) smart glasses and headsets enable users to merge the real world with virtual environments by projecting images onto transparent displays.

The effectiveness of AR devices relies on providing high-quality visuals with a wide field of view (FOV) while being lightweight and compact. A key technology in augmented visualization is the waveguide combiner, which includes input, output, and exit pupil expansion (EPE) gratings.

Here, we discuss the fabrication of these couplers using diffractive gratings that are modulated by duty cycle, depth, and structure. The primary challenge is to achieve a minimal and uniform residual layer thickness, ideally using a high refractive index resist, across gratings with different fill factors to maximize efficiency and FOV. Our method involves creating a waveguide combiner with modulated duty cycle, depth, and structure using high-performing high-refractive-index nanoimprint materials from INKRON and inkjet printers and nanoimprint equipment from SUSS. Using interference imaging and scanning electron microscopy (SEM), we highlight the benefits of inkjet-printing the nanoimprint resin over traditional spin-coating processes. We focus on precise control of the residual layer, achieving thicknesses as low as 50 nm with excellent uniformity throughout the waveguide combiner.

Introduction to waveguide combiners for augmented reality

Augmented reality (AR) smart glasses and headsets offer users a unique blend of their natural environment and virtual worlds by projecting images onto a transparent display surface, creating an immersive interaction and visualization experience.

To ensure an optimal user experience, AR devices must meet stringent criteria: delivering high-quality images with a large and uniform field-of-view (FOV), a spacious eyebox, and superior color fidelity, all while maintaining a lightweight, compact design. Not to mention, the design approach needs to be suited for large volume manufacturing and meet the price levels in business or consumer markets.

Waveguide combiners based on diffractive surface relief gratings (SRGs) made by nano-imprinting using special high refractive index (HRI) resin materials have been shown to offer an optimal combination for AR waveguide manufacturing. Despite the proven technology, improving the display qualities even further requires advancements in optical designs, which are enabled by manufacturing and material innovations [1].

SRG waveguide combiner designs, which typically comprise of input, output, and exit pupil expansion (EPE) gratings, have been developing towards more complex grating structures such as modulated gratings. Also, generally, the SRG waveguides benefit from a higher refractive index of the glass substrate and the patterned imprint materials. However, the direct imprint materials meeting the requirements of AR waveguide manufacturing (excellent replicated pattern fidelities, low shrinkage and stable manufacturing process) have been practically limited to refractive indices lower than 2.0, and in case of fully photostable materials significantly lower. Therefore, in designs with substrate refractive indices higher than that of the imprint material, the thickness of the imprint material beneath the grating structures – the residual layer thickness (RLT) – starts to play a pivotal role in achieving the best optical quality.

High quality AR waveguides are characterized by the following properties:

1. Good light coupling and propagation ensure bright, clear, and uniform images while enabling compact and efficient device designs. These factors are crucial for high-performance AR displays and extended battery life.

2. A high diffraction efficiency in AR waveguides assures that the maximum amount of light is directed towards the user's eyes, resulting in brighter and clearer images. This efficiency is crucial for maintaining image quality, reducing power consumption, and enabling more compact and lightweight AR devices.

3. A high color fidelity is needed so that the colors displayed are accurate and true to life. This accuracy enhances the realism and immersion of the AR experience, making digital content blend seamlessly with the real world.

4. The angular dependence affects how light is coupled into and propagates through the waveguide. Proper angular management ensures that light enters the waveguide efficiently and travels with minimal loss and distortion, which is crucial for maintaining high image quality and brightness.

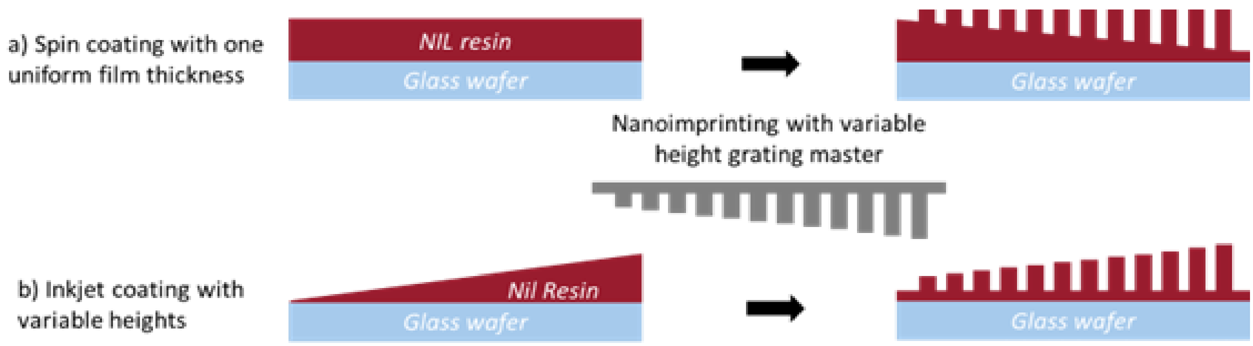

Figure 1: Examples of imprinting modulated grating structures into (a) spin coated film and (b) ink jetted resin where the resin thickness is matched to the structures.

Non-uniform residual layer thicknesses negatively affect these properties, especially with non-matched refractive indices of substrate and resin. To minimize the effects of the residual layer thickness, it needs to be controlled and minimized, preferably to below 50 nm.

Nanoimprinted diffractive SRGs have been typically manufactured with high refractive index nanoimprint resins, which are applied onto glass wafers by spin coating. Spin coating is an established and reliable method to apply the material, but it can be used to coat a wafer with only one uniform film thickness.

The different grating areas have varying pattern depths and fill factors, and to optimize the optical performance, modulated SRGs can have either variable grating height profiles or variable linewidths, sometimes even both. Therefore, when spin coating is used as the application method to fill all the structures, the film thickness must be selected based on the highest gratings profiles in all of the grating areas. When the same film thickness is used to nanoimprint the more shallower grating profiles, they will have higher residual layer thicknesses, which leads to non-uniform residual layer thickness in the other gratings, and reduced optical performance of the SRGs (Figure 1a).

With ink jetting as the application method, the need for variable film thicknesses during nanoimprinting can be considered. Ink jetting allows to deposit variable film thicknesses in a closed layer on the wafer using grayscale ink jetting approach where the film thickness can be optimized for each nanoimprinted height profile. This results in a uniform residual layer film thickness even with variable height grating master (Figure 1b).

This paper explores the importance of selecting appropriate inkjet and imprint equipment from SUSS for fabricating high-quality waveguide combiners, as well as choosing inkjet-capable and high-performing high-refractive-index materials from INKRON to effectively address the challenges encountered during the fabrication of SRGs using nanoimprinting. These challenges include achieving precise control over resist thickness and ink concentrations, establishing step- or gradient-based resist profiles within each waveguide, maintaining uniformity and consistency throughout the fabrication process, and identifying materials compatible with the fabrication process.

SUSS inkjet solutions

We now want to describe why SUSS inkjet technology is perfect for overcoming the challenges described above.

First of all, a brief explanation of the inkjet technology: in inkjet printing, small drops (2 – 80 pl) are applied to the substrate at a very high frequency up to 100 kHz. The drops are fired from so-called print heads, which can contain several thousand nozzles. The applied materials are then usually cured thermally or with UV-light so that they retain their full functionality. Digital images are used as a basis in which the positions of the individual structures are defined as pixels. In addition, the image data can contain other information, such as the locally required layer thickness.

In order to create layers with varying thickness such as steps or gradients, the process must be very well controlled. The most important factors are depicted in Figure 2.

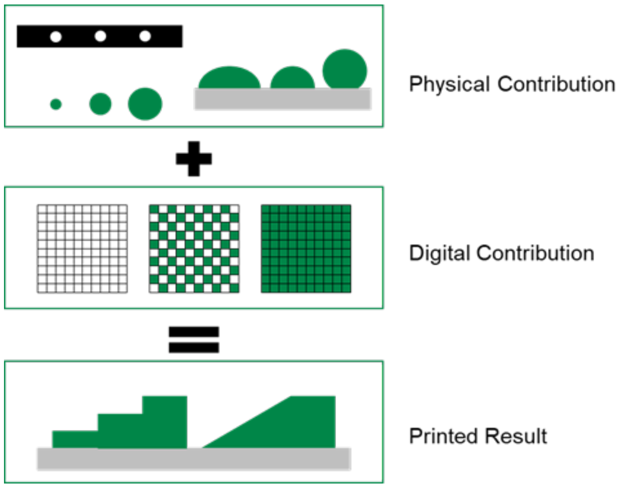

Figure 2: Schematic illustration of contributions to produce steps or gradients.

First, physical properties have to be taken into account. By creating droplets with multiple volumes, the amount of ink can be adjusted locally. This is a feature often referred to as multi-drop or grey scale printing. Next to that the interaction of ink and substrate is of importance. The balance of properties such as surface tension and viscosity of the ink, surface energy, and temperature of the substrate allow to create different properties of the deposited film. This can result in either a homogeneous wetting or narrow, well-defined structures. Once you are able to control the behavior of the ink on the substrate, it is possible to set the digital parameters in order to create the desired patterns. Our inkjet printers are equipped with a wide set of different printing strategies that allow to take advantage of the ink surface interaction. Both physical and digital contributions play an important role in process development and need to be adjusted to fit each other perfectly. In order to support our customers in development and production, we have various inkjet printers in our portfolio (see Figure 3). The LP50 is the perfect process development device. A variety of functions are possible on a compact floor plan, such as drop watching and adjustment of the control parameters. At the same time, our laboratory printer also uses equipment from mass production. This means that the developed processes can be transferred directly to the production equipment. For series production we have the JETx system. Here, the highest precision and reliability are guaranteed on a robust architecture. The system is available in both a manual and an automated version for 200 mm and 300 mm substrates. SUSS has developed various software features and systems to support customers in the various phases of industrialization.

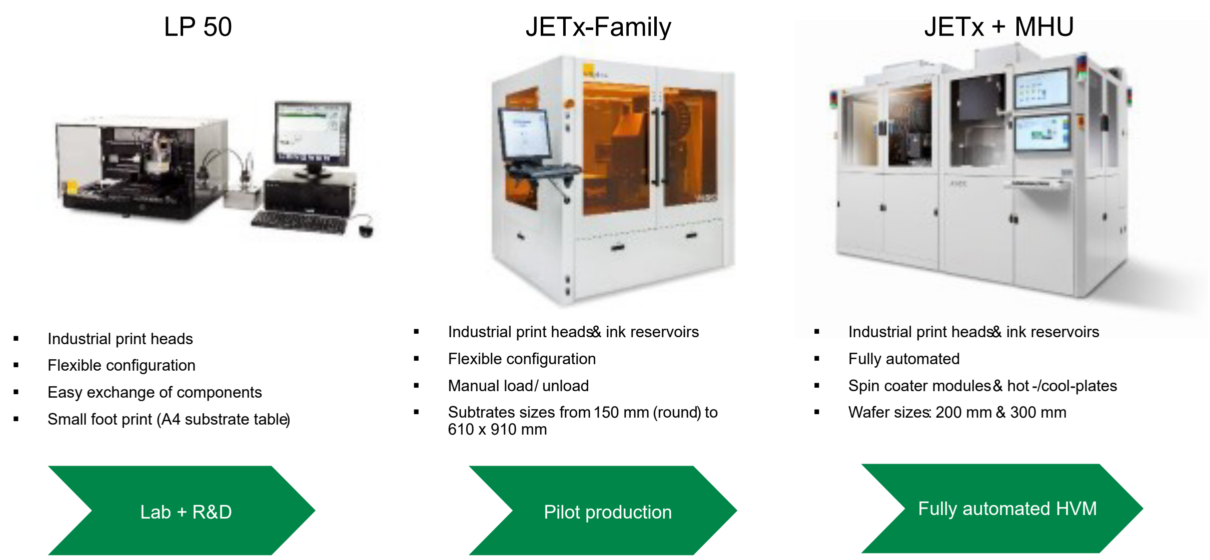

Figure 3: SUSS Inkjet products, ranging from R&D to pilot production and fully automated high-volume manufacturing (HVM).

Inkron ink-jettable nanoimprint material solutions

Inkron is a chemical company focused on developing optical materials for various applications, including AR waveguides, LED packaging, and wafer-level packaging options. High refractive index nanoimprint resins for diffractive waveguides have been one of the key product families that Inkron has been developing for many years. These products are based on Inkron's proprietary siloxane polymer and nanoparticle technology, with both components developed and manufactured in-house to achieve the best possible results, including excellent nanoimprint stability and optical performance.

The first high-refractive-index nanoimprint resins developed by Inkron were made to be applied by spin coating, and Inkron offers a broad product family, ranging from low (N_D 1.55) to high (N_D 1.92) refractive index resins. In recent years, Inkron has developed a new family of these nanoimprint resins for inkjet applications. The main goal of the new ink-jettable resin development was to replace spin coating by ink jetting, while maintaining identical imprinting performance with the corresponding spin coatable products. To cover the needed resin thicknesses arising from the various SRG structures, one of the key targets for the jettable products were to be able to inkjet uniform thin film thicknesses ranging from tens of nanometers to a few hundred nanometers with good patternability. To achieve this, the materials had to be solvent-based, incorporating a mixture of polymer resin and nanoparticles, which required extensive research and development to ensure they were suitable for ink jetting with established compatibility with the common industrial printheads, good and stable jetting properties, and good wetting properties on the substrates.

Inkron now offers a wide range of ink-jettable nanoimprint resins, with refractive indices starting from 1.58 and going up to 1.90. These materials have been optimized to work with multiple printhead types, such as those manufactured by Konica Minolta, Xaar, and Fujifilm, among others. These products were also developed to support grayscale inkjetting, allowing easier control over film thicknesses and enabling optimization of the film thickness based on the waveguide grating profile designs.

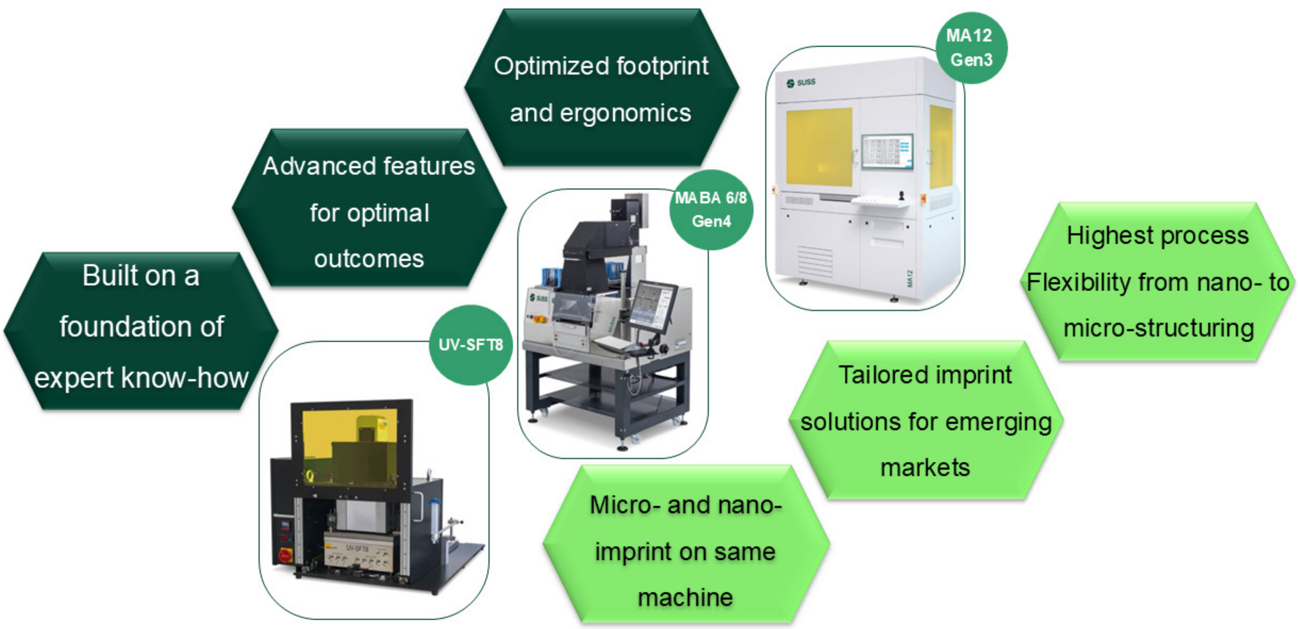

Figure 4: SUSS imaging systems solutions

SUSS imprint solutions

The fabrication process of diffractive waveguide combiners with varying fill factors with a uniform and precisely controlled residual layer thickness can be divided into three distinct steps:

1

Stamp fabrication

The SUSS UV-SFT8 stamp fabrication tool enables the manufacturing of high-quality composite working stamps. Here, the liquid stamp material is dispensed onto a structured master with a protective anti-sticking layer and attached to a flexible backplate. Subsequently, the liquid stamp material is cured by ultraviolet (UV) light and the stamp is demolded from the master.

2

Inkjet printing

Utilizing the SUSS LP50 inkjet printing system, HRI resin from Inkron (IPO-912) is applied to silicon or glass substrates with freely designable print layouts and locally varying volumes. To ensure a stable printing process with accurate volume deposition, it is essential to tune the print head to match the properties of the HRI resist. Moreover, the LP50 facilitates automatic alignment of the printhead to the wafer, ensuring spatially precise deposition that matches well with the stamp design in the subsequent nanoimprint process.

3

Nano imprinting

Equipped with the established SMILE technology [5], the SUSS MABA8 Gen4 and MA12 Gen 3 enable substrate-conformal imprinting of nanostructures into imprint resists, ensuring high transfer fidelity. An automatic alignment process allows precise alignment of the inkjetted resist layout and the working stamp. The stamp is first brought into contact with the center of the substrate and then the contact is radially expanded to minimize defects. The structured high RI resist is cured by UV light followed by the demolding of the stamp within the machine, allowing for high throughput.

Results

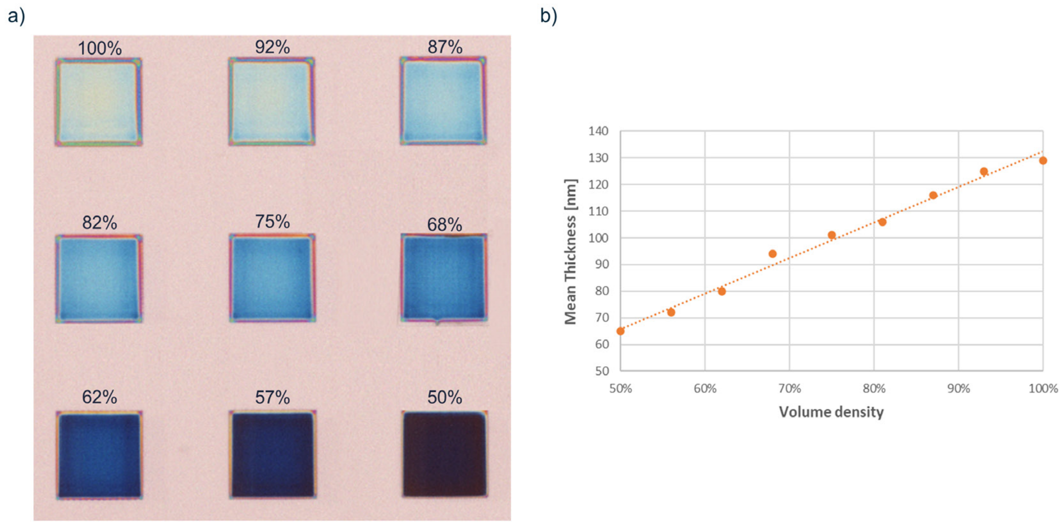

Figure 5: a) Jetted dies with varying volume densities and b) the measured mean thicknesses of the jetted resin.

As discussed above, the residual layer thickness of waveguide couplers plays a crucial role in the optical performance of an AR device. Ensuring consistent residual layer thickness across the in-coupler, EPE grating, and out-coupler is essential for maintaining uniform optical behavior and performance throughout the device. Achieving precise local control of the resin layer thickness using Inkjet Printing is vital to accomplish a consistent residual layer. One way to adjust the amount of locally deposited ink is by varying the print resolution. For example, the Print Head KM1024i has a native resolution of 360 npi (in x-direction) and 90 npi (in y-direction). However, resolution adjustments are limited to multiples of the native resolution, such as 360x360 dpi and 360x450 dpi, already resulting in a 25% increase in deposited ink volume. For this reason, fine adjustment of layer thickness is not feasible with this approach. We have, therefore, developed another method that allows us to change the locally deposited volume per area without changing the resolution. The optical microscope image in Figure 5 shows 4 mm x 4 mm areas printed using this method with an underlying resolution of 360x360 dpi after pre-baking. The deposited volume per area varied between 50% and 100%, yielding film thicknesses from 65 to 130 nm.

Based on the linear relationship between the printed volume per area and the layer thickness shown in Figure 5b, the film thickness can be precisely controlled on nanometer-level. Thicker or thinner layers can

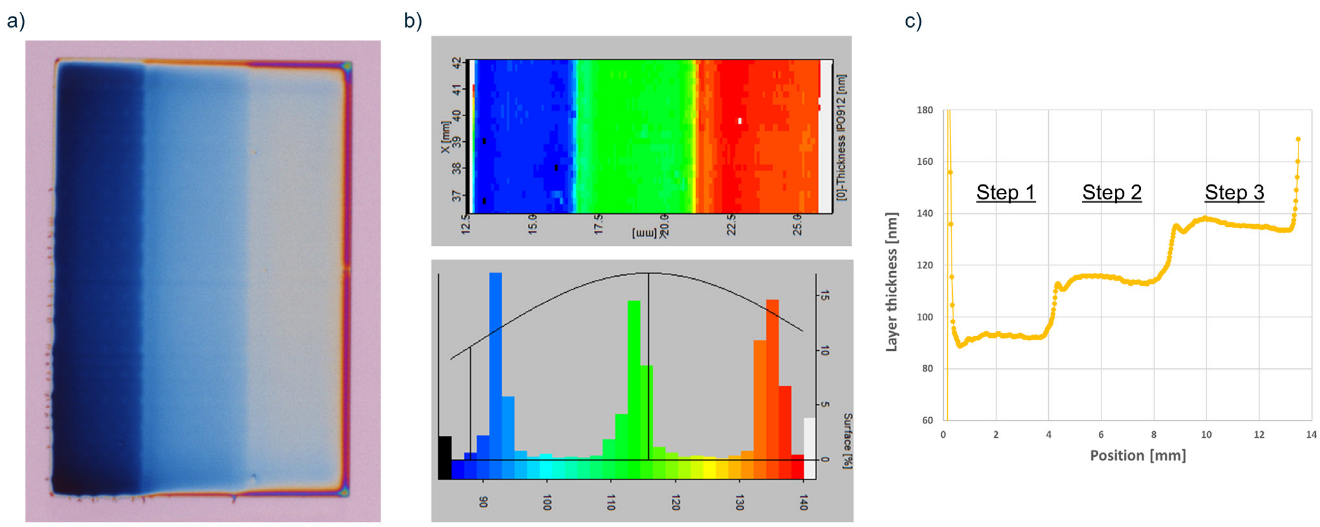

Figure 6: Inkjet printed film with three distinct thickness steps: a) high resolution photo, b) thickness map and histogram measured with a reflectometer, and c) thickness profile across the steps.

be adjusted using this method either by additionally changing the resolution or by adjusting the solid content of the ink.
In addition to varying fill factors and grating depths between individual couplers, gratings often exhibit additional structural complexity, involving the modulation of the depth or duty cycle. This modulation enables precise control over diffraction efficiency at each location, determining the amount of light diffracted out or into the waveguide at specific wavelengths and angles. Such control is essential for tailoring the device's optical uniformity and image quality. From a process perspective, modulating the depth or duty cycle of the gratings alters the volume required to completely fill the grating and its residual layer thickness. Therefore, the deposited volume must be adjusted within couplers to maintain a uniform residual layer thickness. Consequently, the ink typically needs to be printed in the form of steps or a gradient.
For the Inkjet process, a corresponding step print pattern with a size of 4.67 x 20 mm per step was generated, adjusting the volume per area for the steps to 50%, 75%, and 100%.
In Figure 6a, a high-resolution photo of the step thicknesses after pre-baking is shown. The distinct color differences, ranging from blue (50%) to light blue (75%) and nearly transparent (100%), visually indicate the different thicknesses. To further investigate, a thickness map was measured using a reflectometer, as shown Figure 6b. The thickness map clearly shows the three distinct steps, with average thicknesses of 92.0 nm (50%), 113.9 nm (75%), and 134.7 nm (100%). High thickness uniformity is achieved for each step, with 3σ values of ±3.4 nm (50%), ±3.3 nm (75%), and ±4.1 nm (100%) identified in the corresponding histogram. The achieved thickness uniformity is particularly important as it directly influences the resulting residual layer thickness after SMILE nanoimprint. For a more precise determination of the transition region size between steps, we plotted the data as a thickness profile in Figure 6c. Both transition regions are smaller than 0.5 mm, allowing only a small portion of the total printing area to fall on these regions, resulting in sharply defined steps overall. Using the same process approach, thickness gradients can be printed. Over a total size of 14 x 20 mm, the volume per area was linearly adjusted from 50% to 100% in the x-direction and a corresponding print pattern was generated. In Figure 7a, a high-resolution image illustrates the resulting thickness gradient after pre-baking. The gradual change in thickness is clearly visible as colors transition smoothly from blue to light blue to nearly transparent, creating a continuous gradient without distinct boundaries. For further investigation, a thickness map was measured using a reflectometer as shown in Figure 7b. In the displayed excerpt of the thickness map, the gradual thickness variation is clearly visible ranging from 80 to 135 nm.

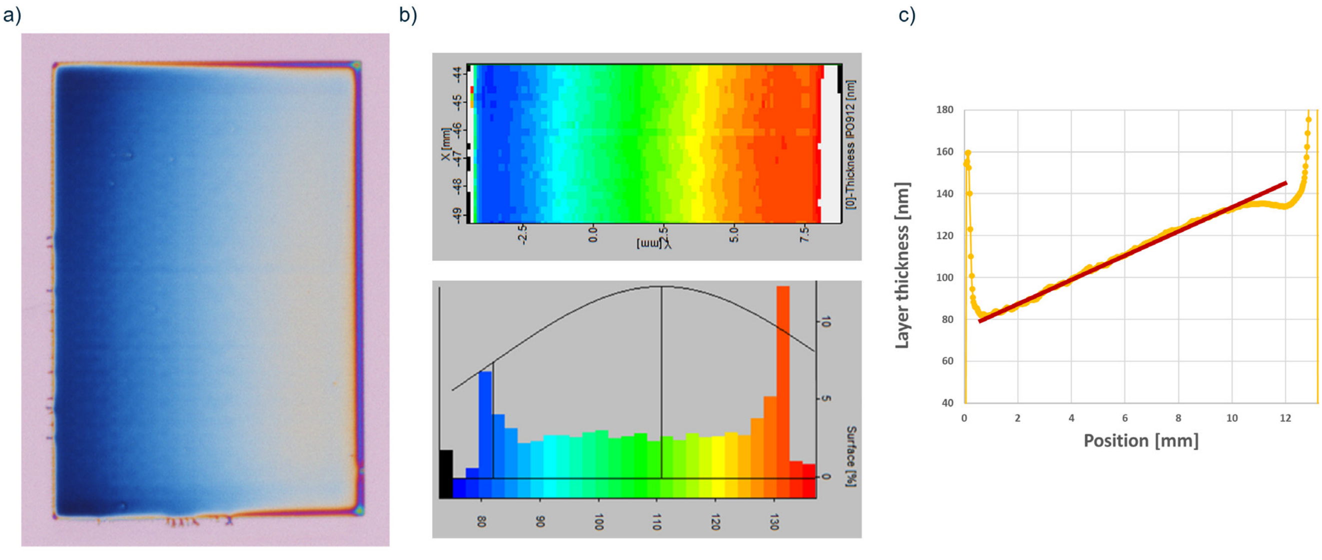

Figure 7: Inkjet printed film with linear thickness gradient: a) high resolution photo, b) thickness map and histogram measured with a reflectometer, and c) thickness profile.

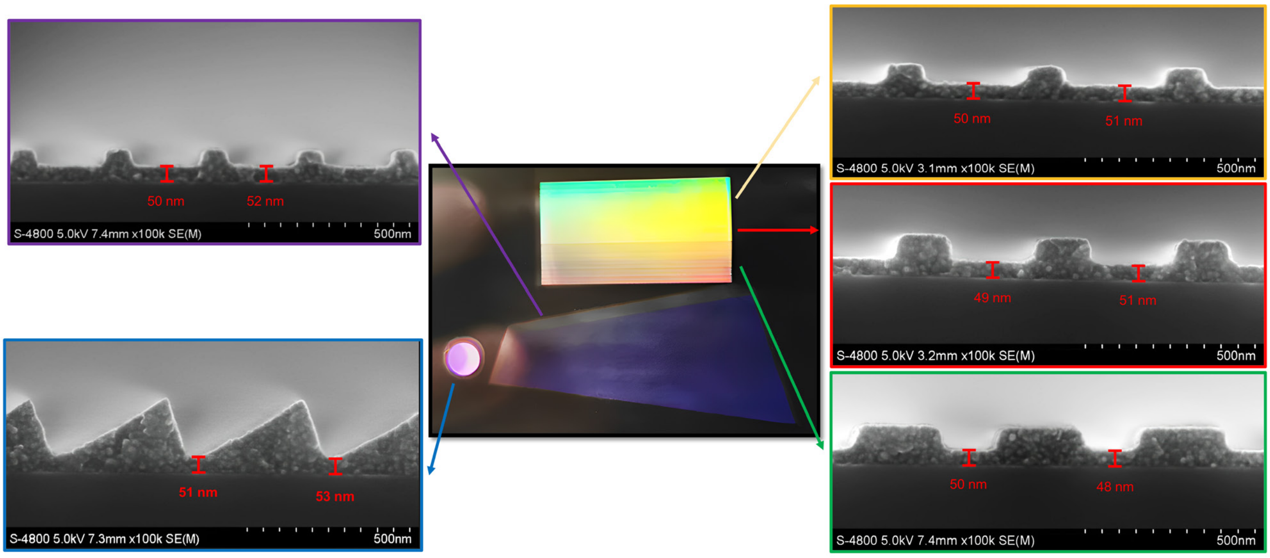

Figure 8: Photo of an imprinted AR combiner alongside SEM images demonstrating a uniform RLT of 50 nm across the IC, EPE, and modulated OC regions.

The corresponding histogram within the analyzed area demonstrates a nearly uniform distribution of thicknesses, indicating a linear thickness progression throughout the analyzed area. However, due to the influence of edge beads, deviations from uniform distribution occur at thicknesses of 80 nm and 135 nm. To precisely determine the linear increase in resist thickness, the data was plotted as a thickness profile in Figure 7c, with a linear reference line (in red) added to the plot. The comparison between the measured profile and the reference line highlights an almost perfectly linear gradient. Only the region near the edge bead at a thickness of ~135 nm deviates from an ideal linear progression, attributed to the significant influence of the edge region. Ongoing collaborative efforts between Inkron and SUSS are currently investigating the resist behavior in edge regions.

Finally, we used our developed process to adjust film thicknesses using inkjet to print the layout of an AR combiner, which was then imprinted with SMILE on MABA8 Gen4. Figure 8 shows a photo of the AR combiner after successful imprinting. Our aim was to achieve a consistently thin residual layer of 50 nm across the entire AR combiner. The AR combiner used here includes blazed gratings as the in-coupler, binary gratings as the EPE grating, and a duty cycle modulated binary grating as the out-coupler. To meet the different local fill factors, the volume per area was adjusted using the inkjet process, e.g. by printing multiple thickness steps for the out-coupler. At the start of the actual nanoimprint on MABA8 Gen4, the inkjetted AR combiner layout was aligned with high accuracy to the working stamp. This alignment is crucial, as any displacement or rotation errors can result in uneven residual layer thickness in the modulated grating. The residual layer thickness was evaluated within the various couplers using SEM measurements on the cross-section. Our target of achieving a uniform residual layer thickness of 50 nm was confirmed at every spot investigated in the combiner.

Summary

The thickness and uniformity of the residual layer in waveguide couplers are crucial for the optical performance of AR devices since a consistent thickness across different components ensures uniform optical behavior.

SUSS inkjet printers and nanoimprint equipment and INKRON resins allow a precise local control of the resin layer thickness at the nanometer level with a matched refractive index of resin and substrate. By locally adjusting the deposited volume per area, steps and gradients in thickness can be printed. The achieved resin uniformity in the printed steps is high with 3σ values down to ±3.3 nm. The developed process was used to print an AR combiner layout, achieving a uniform residual layer thickness of 50 nm across different regions.

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Responsible Department
Application
simon.drieschner@suss.com
+49 89 32007-314

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SUSS MicroTec SE
suss.com