Exploring the boundaries of large-area nanoimprinting for mass production of AR waveguides

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ABSTRACT

Amidst the mixed news surrounding the feasibility of Augmented Reality (AR) smart glasses, the demand for commercially viable mass production of industry-standard optical waveguide combiners remains unwavering. Over the past two years, our consortium of companies has proposed a cost-effective and scalable manufacturing process for Surface Relief Grating (SRG) based waveguides, offering a comprehensive path from concept to fabrication through large-area nanoimprinting. This approach has garnered significant interest from both customers and partners associated with the participating companies. Our aim is to push beyond the established limits of large-area nanoimprinting. In this work we address the obstacles and latest advancements in maintaining imprint quality, fidelity and uniformity during large-area nanoimprinting. We demonstrate various building blocks that are crucial to manufacture high quality and cost-effective AR waveguides, such as the replication of slanted gratings and the possibility of low residual layer thickness using large-area nanoimprint lithography. We employ high refractive index materials, such as resin and glass (1.8, 1.9 and 2.0), and also explore a lighter and flatter version of the RealView 1.9 glass. Our primary objective is to demonstrate that large-area nanoimprinting not only presents itself as a novel method for high-volume manufacturing of SRG waveguides but also enables the production of challenging optics for AR smart glasses.

Keywords: augmented reality, optical waveguides, nanoimprinting, optical design, mastering, high index glass, optical metrology.

1. INTRODUCTION

Leveraging large-area nanoimprinting technology and equipment is crucial for achieving cost-effective mass production of Surface Relief Grating (SRG) waveguides. To demonstrate the advancements and the key building blocks for the Nanoimprint Lithography (NIL) manufacturing of SRG we came together once more as a consortium of companies. Within these building blocks, we include the successful demonstration of slanted gratings replication, the possibility of achieving low residual layer thickness when using large-area NIL, and the use of lower weight & flatter glass substrate based nanoimprinting. We show the key technologies that when combined can create with high quality the crucial components for AR glasses, the waveguides. We show the design of a waveguide and the mastering of blazed, binary and slanted gratings. Then, we point out that high quality high refractive index materials, such as the glass substrate is essential. Using R2P nanoimprint we demonstrate the production of samples with different combinations of materials and textures, demonstrating the versatility of the technique. Finally, we validate the production chain performing metrology on the produced samples and master.

2. KEY TECHNOLOGIES

2.1 Waveguide design (LightTrans)

In the design process of the AR waveguide, a fully rigorous model was employed in the software VirtualLab Fusion. The basic layout of the waveguide is a so-called 1D-1D pupil expansion, which typically consists of three different grating regions (incoupler, exit pupil expander (EPE), and outcoupler, see Figure 1). One of the advantages of this type of layout is the separation of the pupil expansion in two different grating regions: in the EPE (here: horizontally) and outcoupler (vertically) and the application of 1D-periodic (lamellar) gratings (periods: 415 nm for in and outcoupler, 293.45 nm for EPE). The orientations of the grating lines are configured accordingly: incoupler: vertically (0°), EPE: 45°, outcoupler: horizontally (90°). In order to improve the overall efficiency, a blazed grating is used as incoupler, whereas a binary structure is chosen for EPE and outcoupler. For the optimization of the lateral uniformity of the light distribution in the eyebox, the grating parameters were varied continuously in the direction of the desired pupil replication (horizontally for EPE) and (vertically for outcoupler). For binary grating structures in this specific configuration, it turned out that a variation of the grating height in addition to the fill factor is just beneficial for the optimization of the outcoupler, but not for the EPE. Hence, for the EPE just the fill factor was varied laterally. After the optimization, the modulation was discretized according to the demands of the fabrication. The designed waveguide and its parameters are shown in Figure 1. The final waveguide design specifications are: 532 nm design wavelength, FOV: 32°×18°, eyebox: 15 mm × 8 mm; 1D-periodic gratings; refractive index of slab and grating material: 1.9.

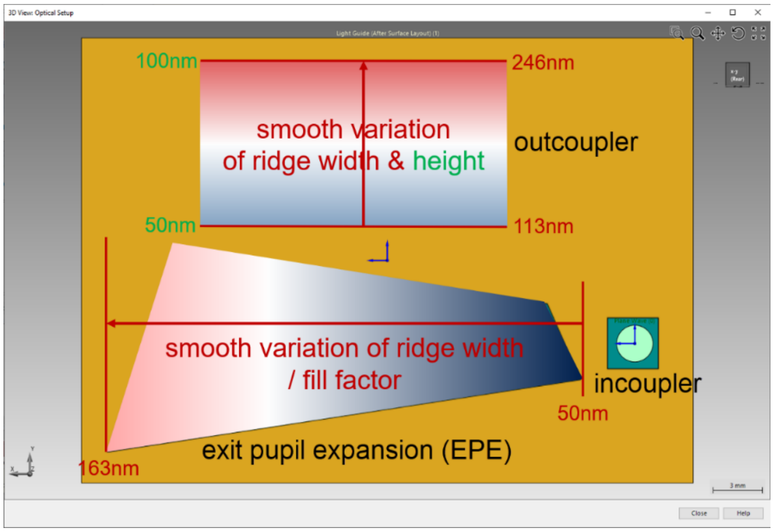
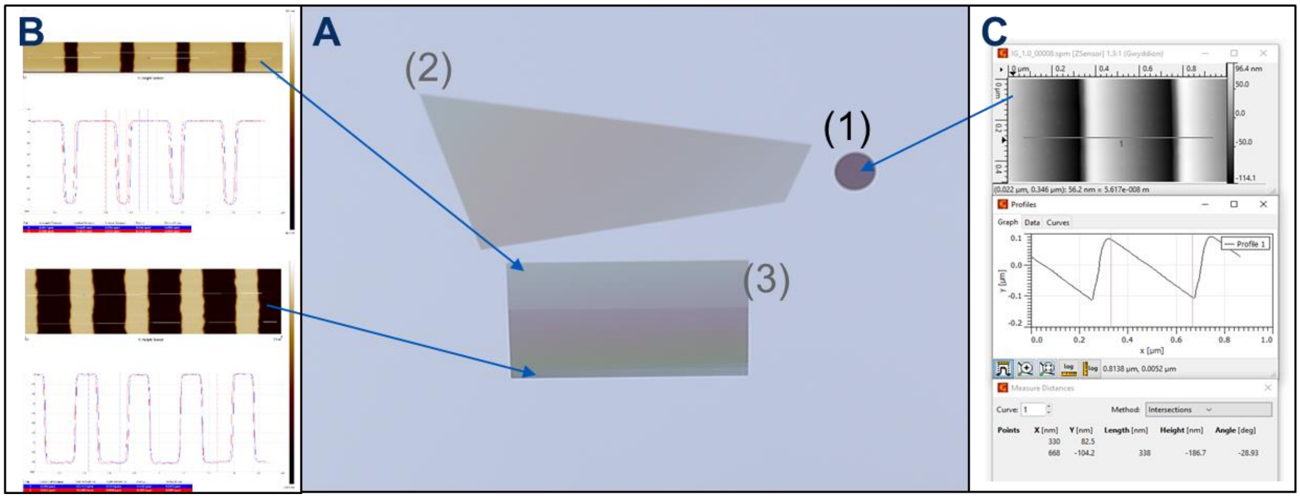


Figure 1 Top view of designed waveguide with 3 surface relief gratings: incoupler, exit pupil expander and outcoupler. The modulation direction of the grating parameters is indicated by red arrows, the optimized values are shown next to the respective region.

2.2 Masters (NIL Technology)

Two types of silicon masters were produced for this work: one full eye-piece SRG waveguide master (designed by LightTrans, see section 2.1) with blazed incoupler grating and binary multi-depth and fill-factor modulated expander and outcoupler gratings (Figure 2), and one test master with 4 slanted gratings each with different orientations (Figure 3). The gratings on the masters are defined by electron beam lithography and transferred into the silicon substrate by proprietary dry etch processes.



(0.022 µm, 0.346 µm): 56.2 nm = 5.617e-008 m

0.8138 µm, 0.0052 µm

Curve: 1

Method: Intersections

Points	X [nm]	Y [nm]	Length [nm]	Height [nm]	Angle [deg]
	330	82.5			
	668	-104.2	338	-186.7	-28.93

Figure 2 (A) Digital camera image of hard master ((1) Incoupler grating, (2) Expander grating, (3) Outcoupler grating). (B) Representative AFM scans of shallow and deep section of binary output grating (note fill factor as well as depth is different). (C) Representative AFM scan of blazed input grating.

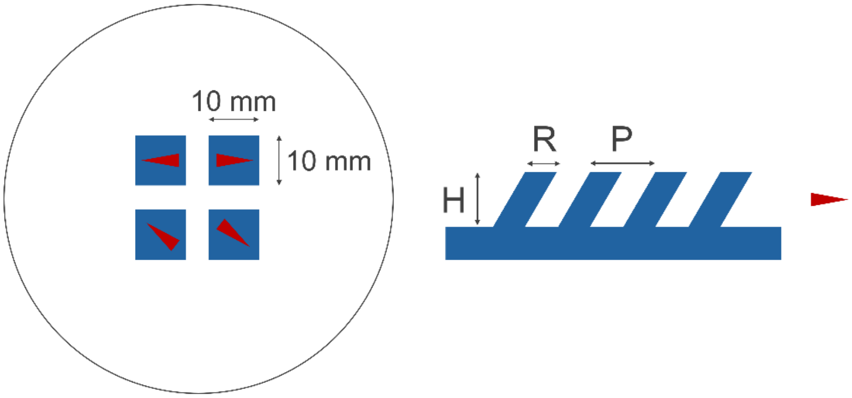


Figure 3 Sketch of slanted grating hard master; Four 1 cm^2 grating areas with different slant directions (indicated by the red arrows). Including cross sectional sketch of each of the four gratings showing the grating parameters.

2.3 Glass substrates (SCHOTT)

The backbone of AR waveguides is specialty grade high-index optical glass. Recent development has extended the RealView glass portfolio to a broad refractive index range beyond 2.0 and formats up to 300 mm round and square, which allows for mass production of high-quality small form factor devices.

A new grade of ultra-flat wafers helps to minimize fluctuation of image quality of diffractive waveguides and enables thinner and lighter devices maintaining stunning image quality. In general, the beam path deflections account for the loss of image quality, and local slope and wedge directly correlate to image quality and values were cut in half for ultra-flat wafers. The Ultra grade is now available for the whole RealView portfolio and is the key for weight reduction of AR devices. Thinner wafers can be used as relatively higher number of bounces is balanced out.

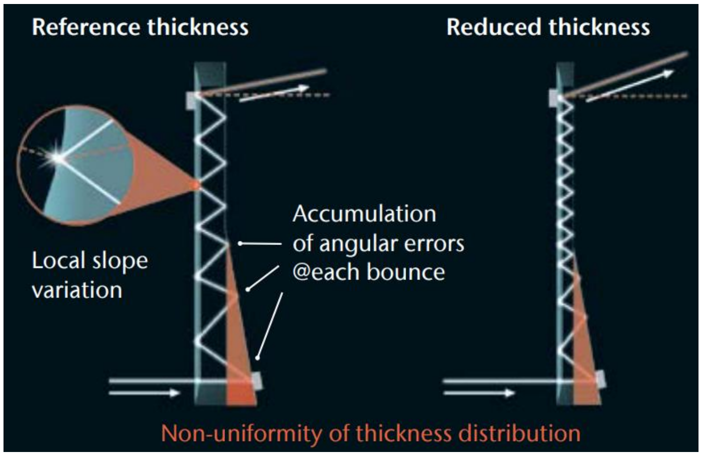


Figure 4 Sketch showing that the waveguide beam paths encounter aberrations when thickness varies, causing local slope and wedge non-uniformity. Thinner waveguides intensify this effect with more bounces.

Video 1 300mm^2 RealView 1.9 refractive index glass on display at the SCHOTT booth during SPIE AR/VR/MR 2024 https://dx.doi.org/doi#here.

2.4 Large-Area Nanoimprinting (Morphotonics)

In order to produce replicas of the aforementioned masters in a repeatable manner, the Roll-to-Plate (R2P) nanoimprint technology of Morphotonics was employed (see Figure 5 (a)). With this technology, a transparent flexible stamp containing the inverted of the desired texture is guided by rollers. The clean substrate (commonly glass) is prepared/sprayed in a primer station, then coated with the desired resin. This substrate is then guided/laminated by the flexible stamp and rollers. The resin is cured with a UV light source (365 nm) and the flexible stamp is then delaminated and an imprinted sample is available. The flexible stamp is proven to last for more than 500 times. Morphotonics' machines can precisely nanoimprint areas of up to 1100 mm x 1300 mm (Gen5), this means that multiple replicas can be made in one cycle. As shown in our previous works, more than 270 waveguides can be imprinted in one machine cycle [1,2], showing that scalability is possible. To ensure dimensional stability, for all imprints High Dimensionally Stable (HDS) stamps from Morphotonics were used.

The imprint quality, such as its fidelity and uniformity, is important for high-quality performance of waveguides. We explored this with the use of different resin formulations from Pixelligent Technologies (including solvent based resins with the use of spin coater) with refractive indices of 1.8, 1.9 and 2.0. The solvent-based resins provide a path to obtain low residual layer thickness (< 100 nm), which could lead to less thickness variations, however, the fidelity of the replicated textures still needs to be further investigated. We also made use of the RealView SCHOTT glass, described in the previous section. The high-quality clean wafers are relevant for the final imprint quality. We made replications using matching resin and glass refractive indices, which shows the versatility on the resins used in the imprint process. Additionally, replications on ultra-flat glass were performed, which can be used to understand the impact of the quality of the substrates on the final waveguide. In Figure 5 (b), a photo of a waveguide imprint is shown.

Another challenging aspect of nanoimprinting of AR waveguides is the replication of slanted gratings. With the use of a test master (Figure 3) with different gratings orientations, we demonstrate the replication of slanted gratings using R2P nanoimprinting. The list of produced samples is presented in Table 1.

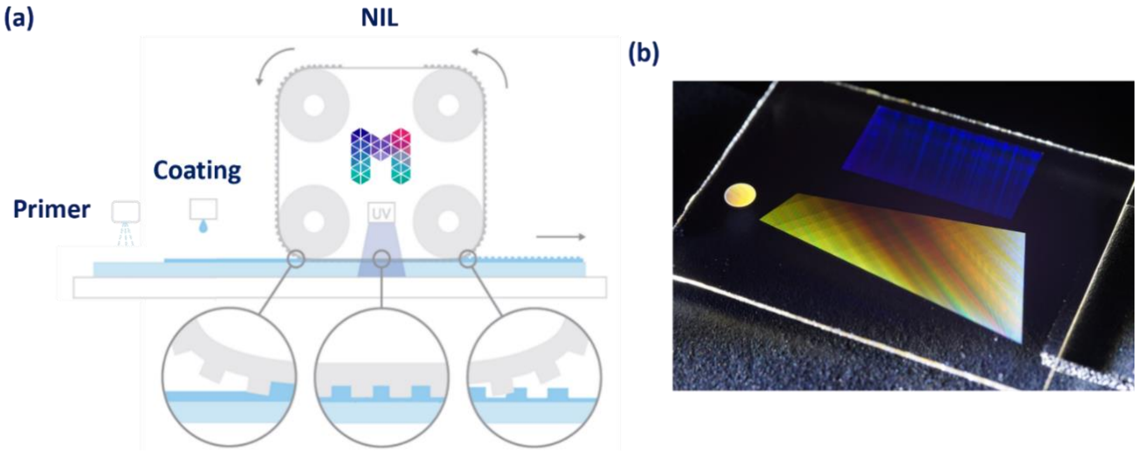


Figure 5 (a) Schematics of a R2P system showing primer, coater and NIL (b) Picture of a imprinted waveguide.

Table 1 List of produced samples.

Nº	Texture type	Resin RI	Solvent-based resin	Glass RI	Ultra-flat
1	SRG Waveguide	1.8	Yes	1.8	No
2	SRG Waveguide	1.9	Yes	1.9	No
3	SRG Waveguide	2.0	Yes	2.0	No
4	SRG Waveguide	1.9	Yes	1.9	No
5	Slanted gratings	1.4	No	1.5	No
6	Slanted gratings	1.4	No	1.5	No
7	SRG Waveguide	1.9	No	1.9	Yes
8	SRG Waveguide	1.9	No	1.9	No
9	SRG Waveguide	1.9	No	2.0	No

2.5 Metrology (OptoFidelity)

A Littrow diffractometer is an optical metrology tool for measuring the period (pitch) of a grating and the relative orientation of its grating lines compared to other gratings. It is based on finding the so-called Littrow angle of incidence, where light diffracts back to the illuminating laser from the grating. With high-accuracy rotary stages and a very stable laser, this non-destructive method can reach picometer and arcsecond scale repeatability for the period and orientation measurements, respectively.

For the measurements performed in this work, a laser with wavelength 405.007 nm and beam spot size of Ø ~1.0 mm was used to scan the samples point-by-point. The grating period measurement had a resolution <0.5 pm and accuracy ±70 pm. The grating relative orientation measurement had a resolution < 0.5 arcsec and accuracy ±50 arcsec. In Figure 6, we show a sketch of the measurement setup.

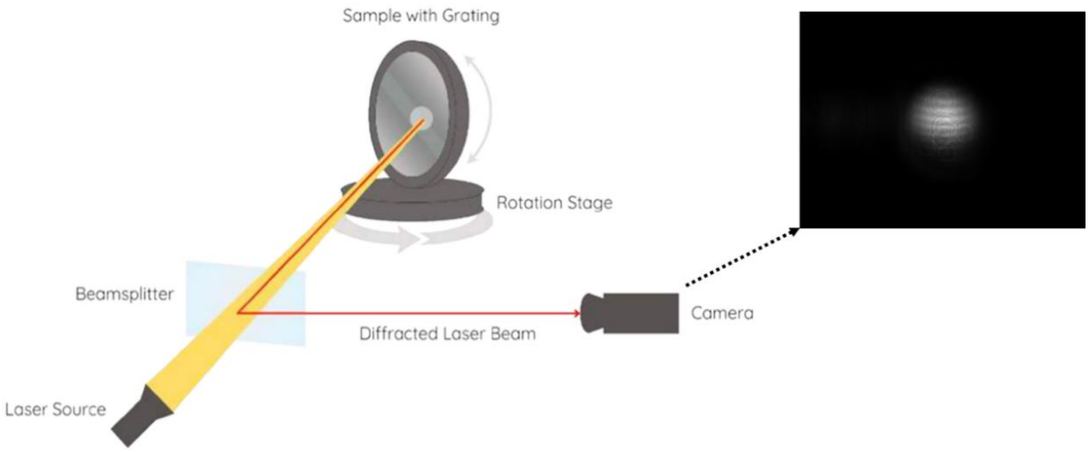


Figure 6 Measurement geometry of the Littrow diffractometer. A laser beam hits the grating, which has been placed on a double rotary stage. At the Littrow angle the beam reflects back to the laser and it is observed with a machine vision camera.

3. RESULTS

A summary of the results of the Littrow measurements for samples 1-4, waveguide imprints with matching resin and refractive index, are shown in Table 2. The incoupler grating (IC) was scanned with 0.5 mm step. For the outcoupler grating (OC) and expander grating (EPE), the step was 1.0 mm. This grating uniformity data was then averaged to obtain the results shown in Table 2.

The average error or the grating period compared to the design value was 40 pm, which is already better than the calibration accuracy of the used Littrow diffractometer, ±70 pm. The maximum deviation from the designed relative grating orientation was 50 arcsec for Sample 4, which is also below the ±50 arcsec accuracy of the used measurement system.

In Figure 7, we show an example result of grating period uniformity using the the outcoupler grating of sample 4. Since the grating design had constant grating period and orientation for each grating area, this data provides a direct measure of the quality of the fabrication process. From the figure we observe the typical effect that the largest deviations of the grating period occur at the edges of the grating.

Table 2 Summary of results for Samples 1-4. Designed periods are 415 nm for incoupler and outcoupler and 293.45 nm for EPE.

Sample	Position	Average period (nm)	Period std (pm)	Average relative angle (deg)	Angle std (arcsec)
1	IC	414.93	32.15	44.9967	9.90
	OC	415.02	34.79	-45.0038	3.65
	EPE	293.43	8.98	0.0017	5.59
2	IC	414.92	34.03	44.9984	6.14
	OC	414.98	13.39	-45.0027	2.84
	EPE	293.42	3.70	0.0018	2.90
3	IC	414.91	27.66	44.9960	6.00
	OC	414.99	31.44	-45.0041	3.74
	EPE	293.41	5.13	0.0009	2.45
4	IC	414.85	34.02	44.9864	8.23
	OC	415.03	17.78	-45.0126	2.77
	EPE	293.41	3.91	0.0004	2.73

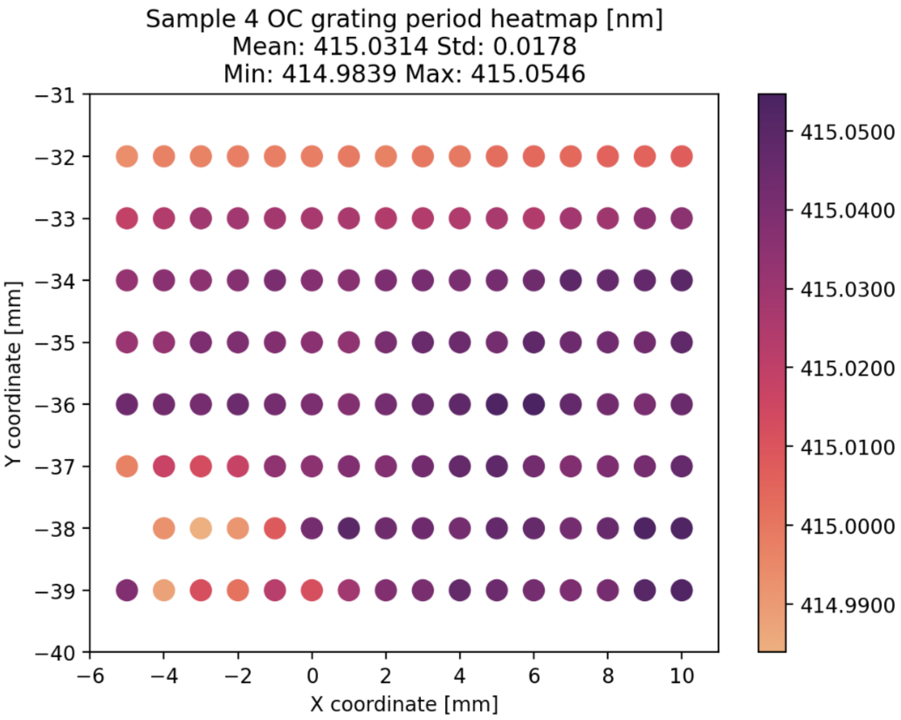


Figure 7 Grating period uniformity for Sample 4 outcoupler grating.

For sample 5, a slanted grating imprint, a grating period uniformity of 20 pm (std) was found. Additionally, the grating relative angle uniformity was below 7 arcsec (std) and the average period accurate to within 20 pm. This is an excellent results as it is within the publicly stated manufacturing requirements of the AR waveguide industry.

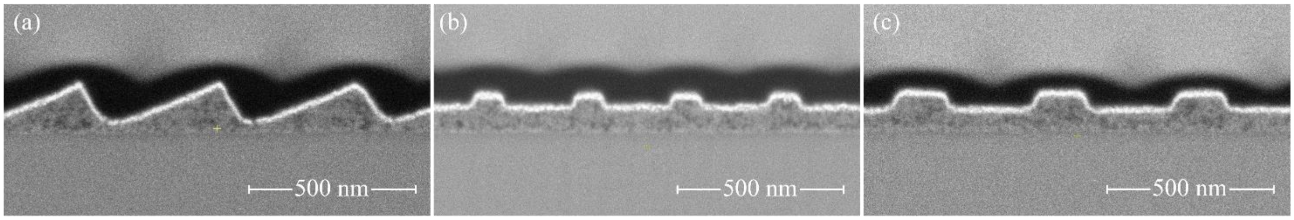


Figure 8 Scanning Electron microscope (SEM) images of a waveguide imprint made on a Silicon wafer using Pixelligent solvent-based resin (1.8 refractive index). (a) Incoupler grating, (b) expander grating, and (c) outcoupler grating.

Additionally, a waveguide was imprinted using large-area nanoimprinting and the solvent-based 1.8 refractive index Pixelligent resin, which resulted in a residual layer thickness of <100nm as shown in Figure 8 and Figure 9. The findings underscore the efficacy of large-area NIL in achieving both uniformity and low residual layer thickness with high refractive index resins.

Figure 9 Picture of the waveguide imprint made with a solvent-based resin on a silicon wafer using R2P technology

4. CONCLUSION

Our study shows significant correlation between the designed parameters via mastering and the achieved characteristics in the final imprinted SRG waveguides. The R2P process is reaffirmed as a robust and effective approach for scaling SRG waveguide production, emphasizing its reliability in achieving consistent outcomes. Furthermore, the successful demonstration of slanted gratings highlights the versatility and capability of large-area nanoimprinting to accommodate intricate structural features. In addition, adaptability to successfully process ultra-flat and lightweight glass showcase the potential to extend beyond traditional materials. These findings collectively underscore the significance of large-area nanoimprinting process in achieving precision and scalability for mass production of AR waveguides.

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