Standard of Procedure - Printing Microlens

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1 Standard of Procedue

1.1 Process flow and optimization metrics

The process of microlens fabrication includes three processes - File generation, 3-D printing, and Lens Optimization. Each step has its critical factors, and we design corresponding metrics and characterization strategies to evaluate those factors (Figure 1).

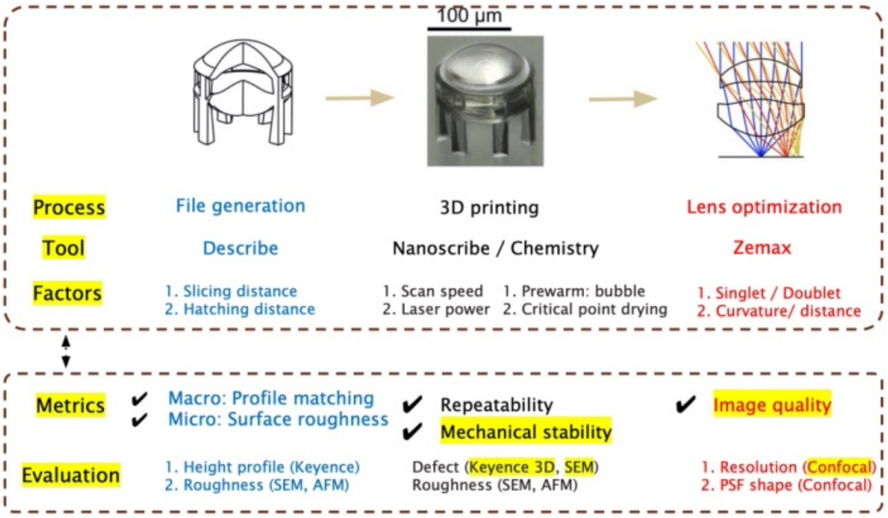


Figure 1: Process flow and optimization metrics for the microlens experiments. Each process includes corresponding metrics and evaluation methods.

The STL files could be generated from 3-D CAD software(AutoCAD, Solidworks, TinkerCAD, Blender, etc.). We chose Zemax OpticStudio for STL file generation because of its powerful and convenient ray tracing and image simulation capabilities. After generating designs with desired curvatures, we added structural supports and outputted the STL files. Describe was used to convert STL files to writing sequences. In Describe, we generated job files and defined parameters, including hatching distance and slicing distance for the writing. The writing laser power and scan speed were defined in the GWL file for the printing. These parameters highly affect writing accuracy and performance.

At the two-photon polymerization stage, the Nanoscribe GT system was used to perform the writing. ITO-coated glasses (25 mm x 25 mm x 0.7 mm, ITO film $\simeq$ 18 nm) were used as the substrate. IP-S negative tone resin (refractive index = 1.478 @ 20°C, Nanoscribe)[**?**] was drop-casted on the conductive side of the substrate for printing. Before printing, the substrate with resin was preheated under 60 degrees on a hotplate. The preheat helps avoid the bubbles in the resin and significantly enhances the printing reproducibility. To perform dip-in laser lithography (DiLL), we loaded the substrate with a DiLL holder and flipped it upside down for insertion. A 25x objective (NA=0.8) with adjustment ring set on ‘Glyc’ and a 780 nm laser were used for the printing. The designed structures are written layer-by-layer with a piezo stage that controls the axial direction, and Galvo mirrors control the lateral direction. After the printing process, the structures are developed with the SU8 developer for thirty minutes and then under isopropanol or HFE-7100 (3M Novec) for ten minutes for washing out the developer.

In micro-optics printing, the surface profile and smoothness matter the most for the optical performance. Therefore, we screened out mainly laser power and scan speed to achieve the best smoothness. The printing results were evaluated in terms of repeatability and mechanical stability with Keyence 3-D microscope and scanning electron microscopy (both 0 and 90 degrees). Keyence Laser confocal microscope provides surface profile. Atomic force microscopy (AFM) and scanning electron microscopy (SEM) reveals the surface roughness information.

To achieve the best functionalities of the microlens, we performed a series of simulation and functionality tests to suggest further optimization. For this purpose, we performed the simulation experiments with Zemax OpticStudio and evaluated the functionalities with imaging and point spread function (PSF) measurements.

1.2 Factors affect microoptics printing

We want to highlight factors especially crucial in the micro-optics printing process:

Slicing distance is the most critical printing parameter because too large slicing distance is the main reason to cause staircase effect (Figure 2). Therefore, we highly recommend setting the slicing distance equal to 100 or 200 nm for micro-optic applications. The hatching distance is relatively less important and could be set to 200 nm to save the printing time.

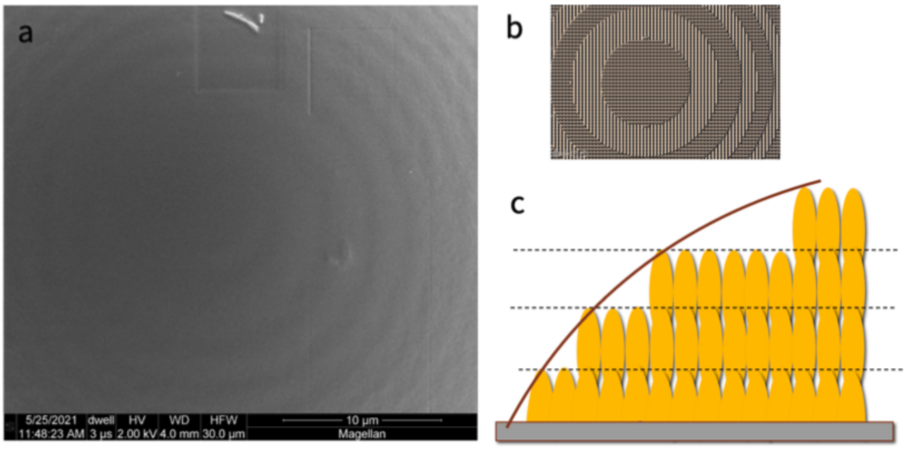
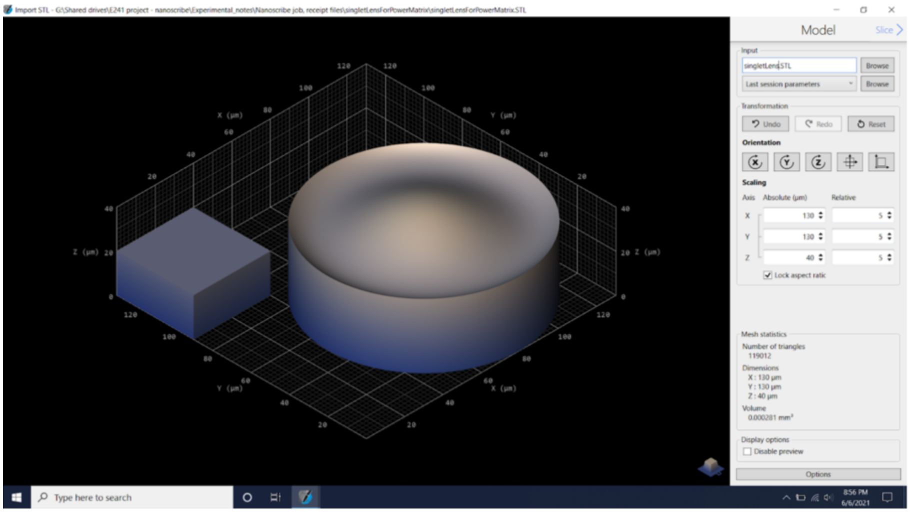


Figure 2: Staircase effect results from the slicing. 2a. SEM image to reveal staircase effect. 2b. A Describe display that defines the staircase when slicing. 2c. Illustration of staircase effect.

1.3 Job file preparation

We start with STL files output from CAD software and demonstrate the writing sequence generation steps by steps (Figure 3).

When we import our STL structures, we could see a display like this. In this display, scaling factors are specified to define the structures on the correct scale. The Describe uses a default unit in micron for STL files, which might cause some design issues. One can visualize one common issue in this step by a very rough structure at this step. This issue suggests that the STL does not include enough mesh points. If this issue occurs, consider drawing the structures larger or define the structures with more mesh points to solve the problem. Another helpful information is volume under the mesh statics, and this value can be used to estimate the rough printing time. In the parameter sets provided in this document(25x objective, IP-S resin, hatching 200 nm, slicing 100 nm), the printing time is roughly 0.013 mm^3/hr. Another valuable tip is to restrict the writing block size within 300 x 300 x 300 um size when using 25x objective. The writing



Input: singletLens.STL

Last session parameters

Transformation

Orientation

Scaling

Axis	Absolute (µm)	Relative
X	130	5
Y	130	5
Z	40	5

☑ Lock aspect ratio

Mesh statistics
Number of triangles
119012
Dimensions
X : 130 µm
Y : 130 µm
Z : 40 µm
Volume
0.000281 mm³

Display options
☐ Disable preview

Figure 3: An example of Describe display after importing a STL file

accuracy slightly deteriorates when writing is close to the block border. Put structures in the center of the writing field if possible. Also, if the structures are larger than 300 um and this would involve multiple writing blocks for the writing. Since stitching between writing fields involves some artifacts, one should beware of avoiding the stitching happening in the functionality part of the design.

We chose the solid mode for our printing to achieve the best structural integrity and homogeneity. We set the slicing distance as 100 nm or 200 nm and the hatching distance as 200 nm for the best prototyping of the printing. The hatching angle is the angle between two consecutive layers for the writing direction. This angle is 90 degrees to minimize a directional artifact inside the structures and retain the shape accuracy. Our structures adopt a constant exposure, but the shell-and-scaffold printing method can also be investigated. For other parameters, one can use the settings below as a starting point (Figure 4). NanoGuide provided by the Nanoscribe company also has a clear explanation for each parameter setting.

After deciding all the parameters for the writing sequence, we will see a GWL file with parameters for the control system. Laser power and scan speed are the most important power to be changed in this window. Next, click "Generate 3D Preview" under the "3D Preview" drop-down menu to estimate the writing time (Figure 5).

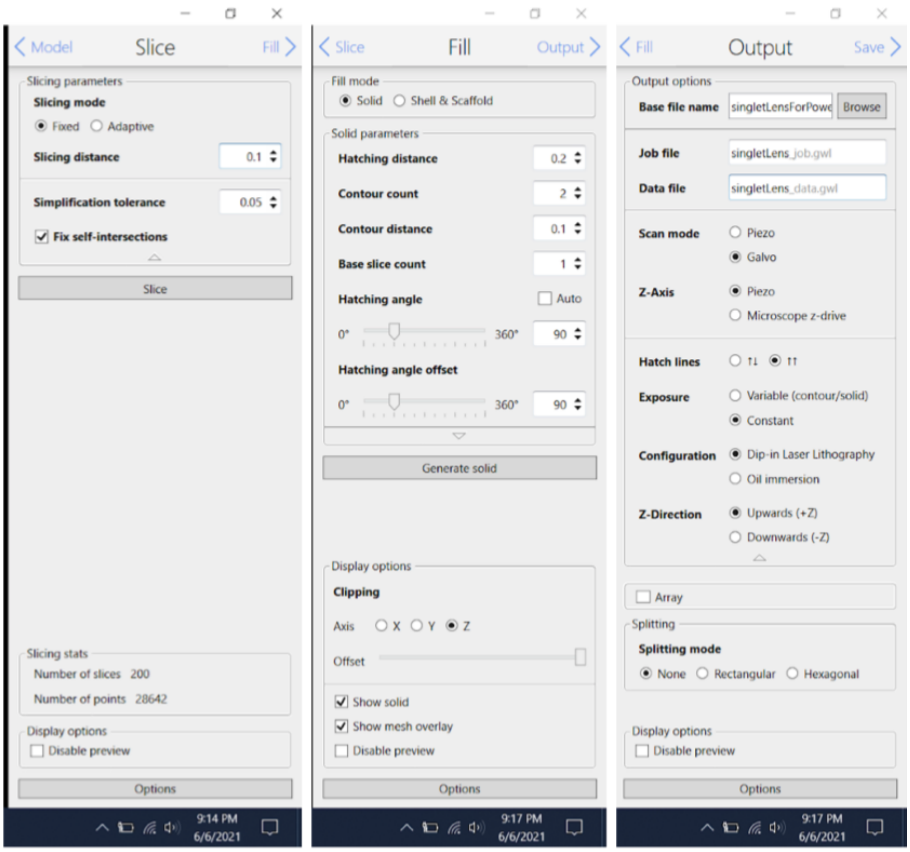
After defining the parameter sweep, one should see the window as below, and it means the parameter sweep file has been successfully created (Figure 6).

1.4 Development

For the development, the standard processing is 30 minutes SU8 developer followed by 10 minutes IPA. Depending on the structural complexity, users could decide the SU8 developer development time to achieve the best efficiency. However, in IPA drying, the tension created by the solvent could potentially collapse the delicate structures. Therefore, several development methods are implemented to deal with this issue and minimize structural deformation during drying.

The first way is using HFE-7100 for drying. HFE (or hydrofluroether) consists of a complex cleaning solvent that does not occur naturally in the environment. The advantage of HFE solvent is having a very low surface tension and could preserve structural integrity.

The second way is using a critical point dryer to remove the IPA. It eliminates surface tension associated with liquid drying by avoiding the phase transition boundary from liquid to gas. Here we show an example using HFE as a rinse solvent to preserve an overhanging structure for microlens.



Slicing parameters
Slicing mode: ● Fixed ○ Adaptive
Slicing distance: 0.1
Simplification tolerance: 0.05
☑ Fix self-intersections
Slice

Slicing stats
Number of slices 200
Number of points 28642

Display options
☐ Disable preview

Fill mode: ● Solid ○ Shell & Scaffold

Solid parameters
Hatching distance: 0.2
Contour count: 2
Contour distance: 0.1
Base slice count: 1
Hatching angle: ☐ Auto 0° 360° 90
Hatching angle offset: 0° 360° 90
Generate solid

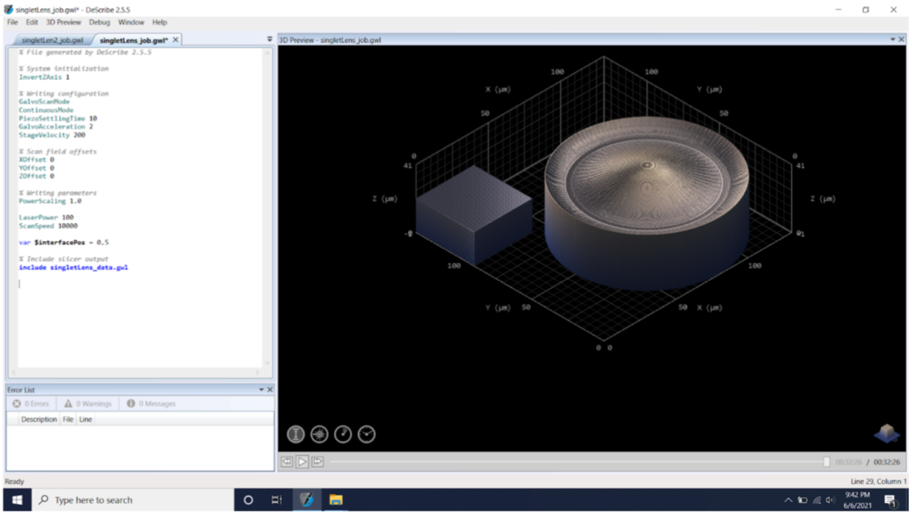
Display options
Clipping
Axis ○ X ○ Y ● Z
Offset
☑ Show solid
☑ Show mesh overlay
☐ Disable preview

Output options
Base file name: singletLensForPowe Browse
Job file: singletLens_job.gwl
Data file: singletLens_data.gwl
Scan mode: ○ Piezo ● Galvo
Z-Axis: ● Piezo ○ Microscope z-drive
Hatch lines: ○ ↑↓ ● ↑↑
Exposure: ○ Variable (contour/solid) ● Constant
Configuration: ● Dip-in Laser Lithography ○ Oil immersion
Z-Direction: ● Upwards (+Z) ○ Downwards (-Z)
☐ Array

Splitting
Splitting mode: ● None ○ Rectangular ○ Hexagonal

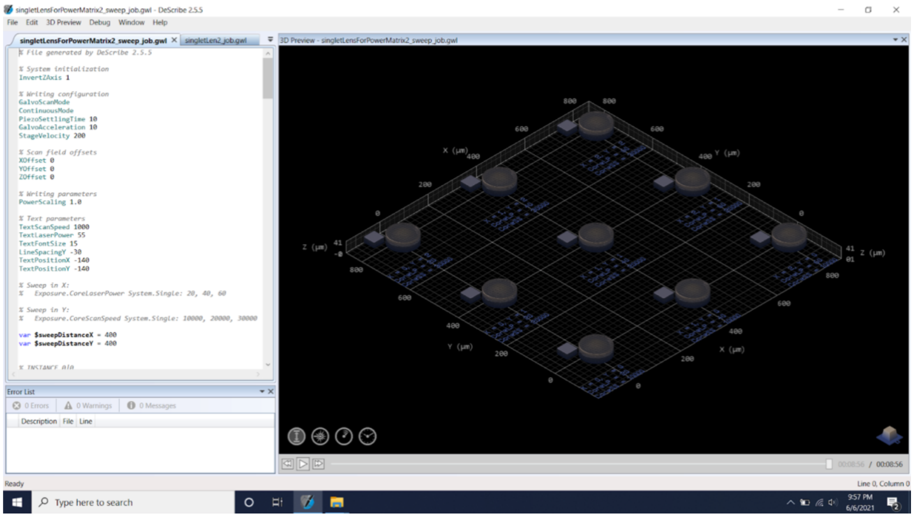
Display options
☐ Disable preview

Figure 4: An example of parameter setting in Describe



```
% File generated by DeScribe 2.5.5

% System initialization
InvertZAxis 1

% Writing configuration
GalvoScanMode
ContinuousMode
PiezoSettlingTime 10
GalvoAcceleration 2
StageVelocity 200

% Scan field offsets
XOffset 0
YOffset 0
ZOffset 0

% Writing parameters
PowerScaling 1.0

LaserPower 100
ScanSpeed 10000

var $interfacePos = 0.5

% Include slicer output
include singletLens_data.gwl
```

Figure 5: An example of GWL code for defining laser power and scan speed



```
% File generated by DeScribe 2.5.5

% System initialization
InvertZAxis 1

% Writing configuration
GalvoScanMode
ContinuousMode
PiezoSettlingTime 10
GalvoAcceleration 10
StageVelocity 200

% Scan field offsets
XOffset 0
YOffset 0
ZOffset 0

% Writing parameters
PowerScaling 1.0

% Text parameters
TextScanSpeed 1000
TextLaserPower 55
TextFontSize 15
LineSpacingY -30
TextPositionX -140
TextPositionY -140

% Sweep in X:
%   Exposure.CoreLaserPower System.Single: 20, 40, 60

% Sweep in Y:
%   Exposure.CoreScanSpeed System.Single: 10000, 20000, 30000

var $sweepDistanceX = 400
var $sweepDistanceY = 400


% INSTANCE 0|0
```

Figure 6: A final display after the advanced STL processing

1.5 Characterization procedure

We establish a series of characterization procedures to evaluate our micro-optics fabrication in the hope of answering a different question based on our designed metrics. This study uses SEM, AFM, laser confocal microscope, and 3D microscope as our main characterization tools. This characterization logic is generalizable for other two-photon polymerization processes.

SEM provides a way to evaluate the surface property and internal structure of the lens. This technique can provide qualitative information of surface property after printing. For example, SEM reveals the staircase effect after printing and helps us evaluate the smoothness of the structures for the following images. We also figure out a 90-degree SEM procedure for the evaluation of the internal structures. The 90-degree SEM is helpful if some residues or deformations exist in the internal structures.

For other tools, AFM can reveal microscopic surface smoothness properties. Keyence laser confocal microscope provides topography and height information, allowing us to match surface profile. Keyence 3D microscope visualizes the lens in multiple angles from 0 degrees (top images) and 90 degrees (side image). Also, Keyence 3D can be operated in a transmissive or reflective mode to provide different contrast.