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# OPTIMAL workshop

Data-driven optimization of laser lithography

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# The University of Parma



UNIVERSITÀ  
DI PARMA



## The University of Parma:

- 1,000 Years of history
- 10 Departments
- 25 Research, training and service centers
- 108 Degree courses
- 111 Postgraduate courses
- 33,000 Students
- 2,000 Faculty and staff members

## The Department of Engineering & Architecture:

- Information Engineering
- Civil & Environmental Engineering
- Architecture

## The Department of Engineering for Industrial Systems and Technologies:

- Mechanical & Management Engineering



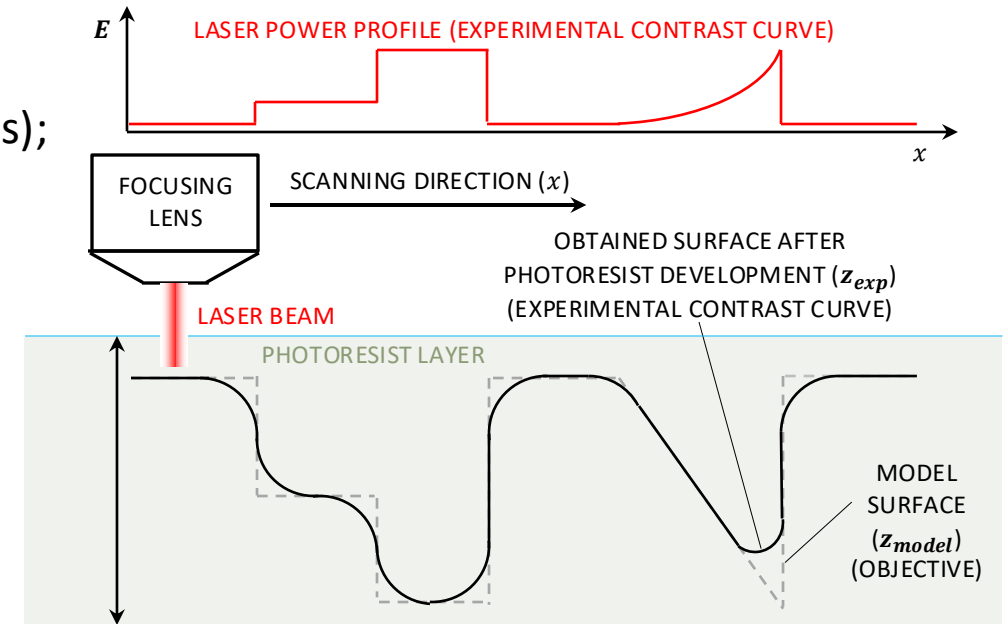
# Introduction

Experimental optimization of virtual photomasks (grayscale exposure images) in maskless grayscale laser lithography typically requires several iterations **for each new geometry** due to:

- Non-linear response of photoresist to exposure dose;
- Proximity effects (variations due to proximity of nearby features);
- Sharp dose transitions near edges and vertices.

**Each iteration** typically requires:

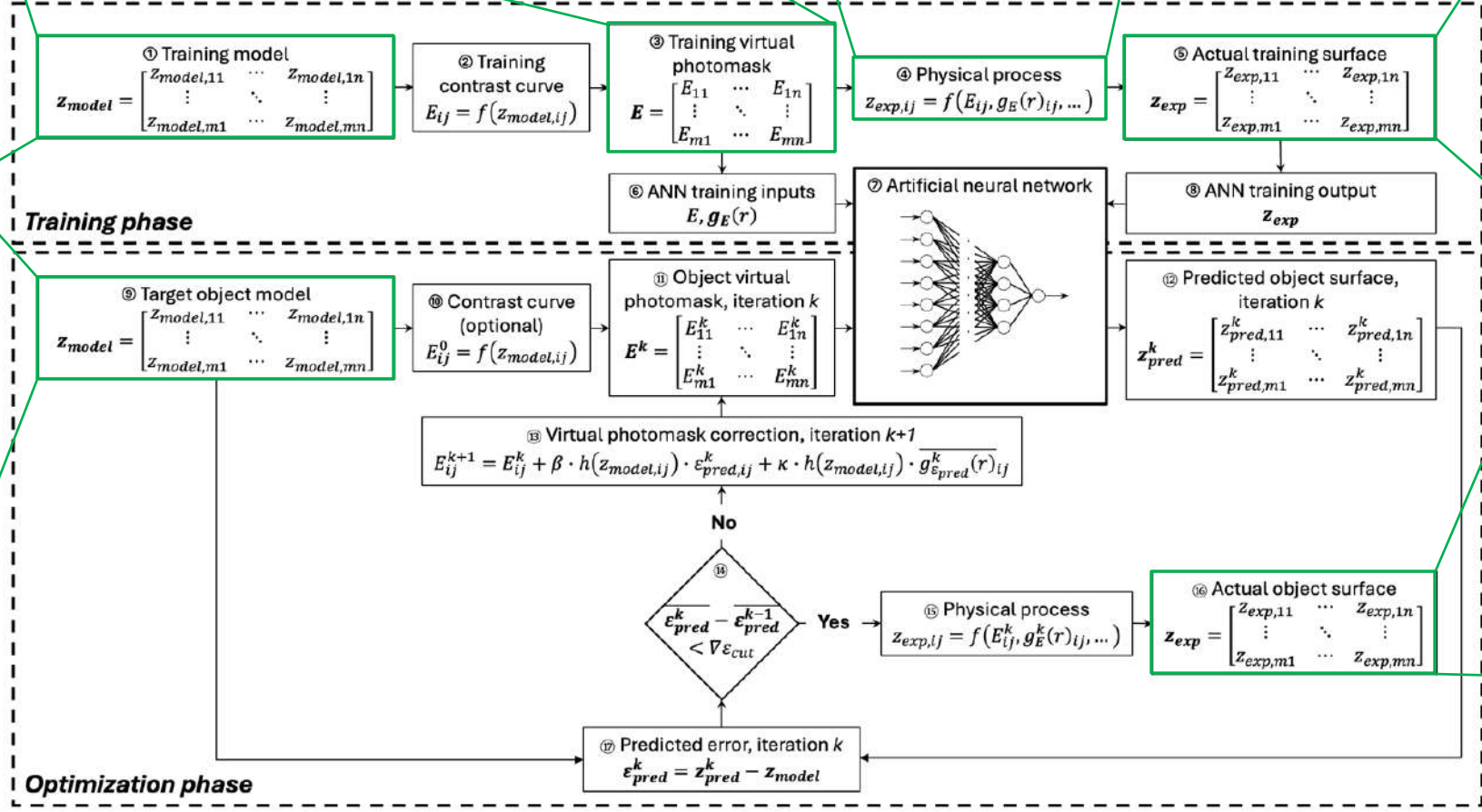
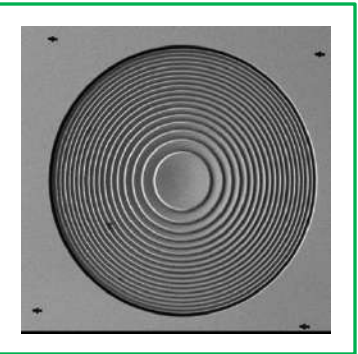
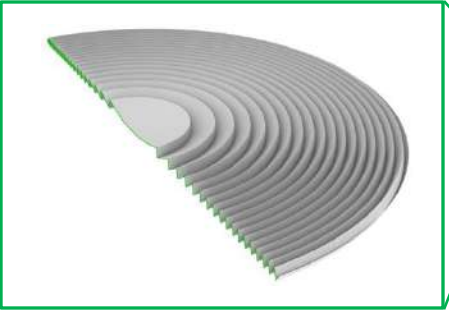
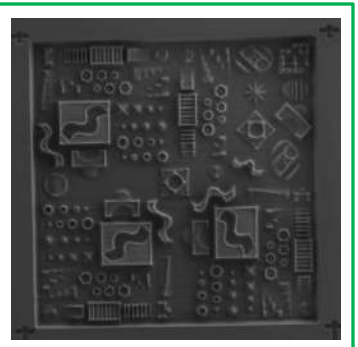
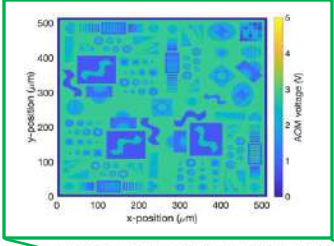
- Photoresist deposition;
- Lithography setup and laser exposure;
- Sample development;
- Topography acquisition and data analysis;
- Revision of virtual photomask.



Commercial software packages such as GenISys BEAMER 3D-PEC employ physics driven representations. These can be **very expensive** and nonetheless **sensitive to experimental calibration and photoresist stability**. Data-driven machine learning (ML) models are effective at handling high dimensional problems to discover causal relationships within data that are not necessarily accounted for in physics-driven models. They can also be more versatile and simpler to implement.

**AIM: To achieve first-time-right manufacturing through data-driven optimization of grayscale laser lithography.**

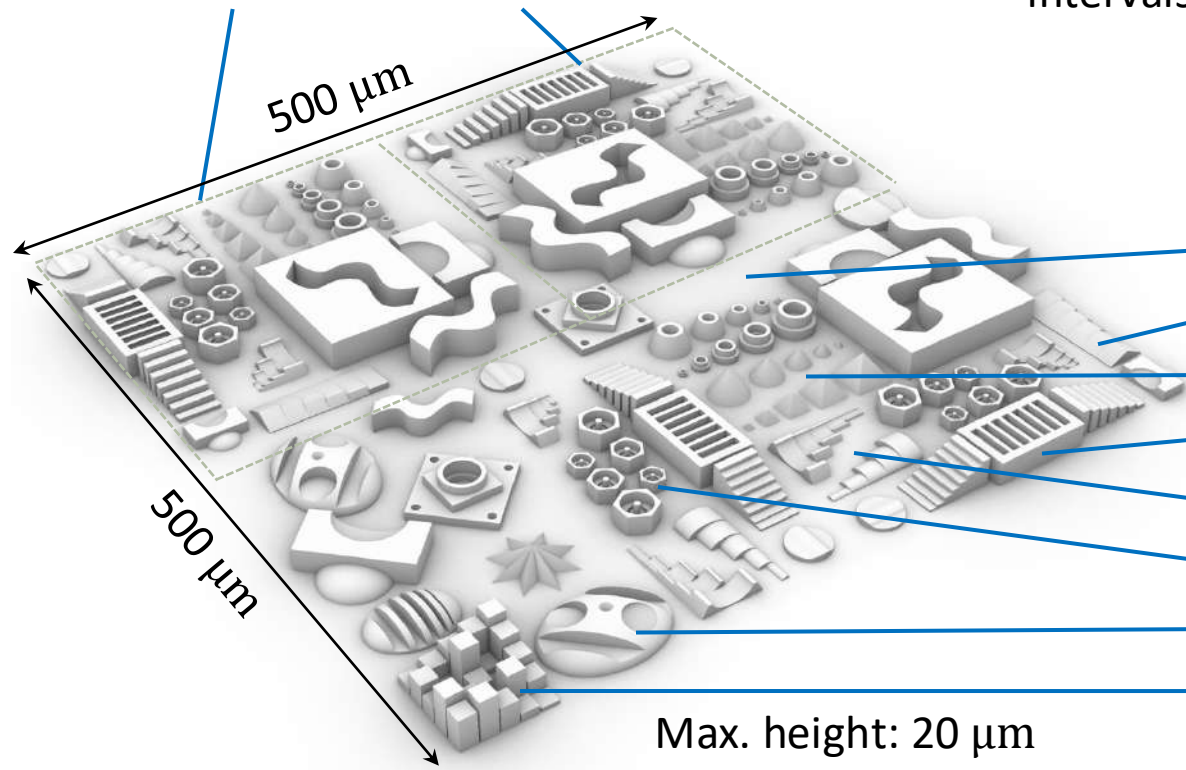
# Data-drive optimization



# Training and test case models

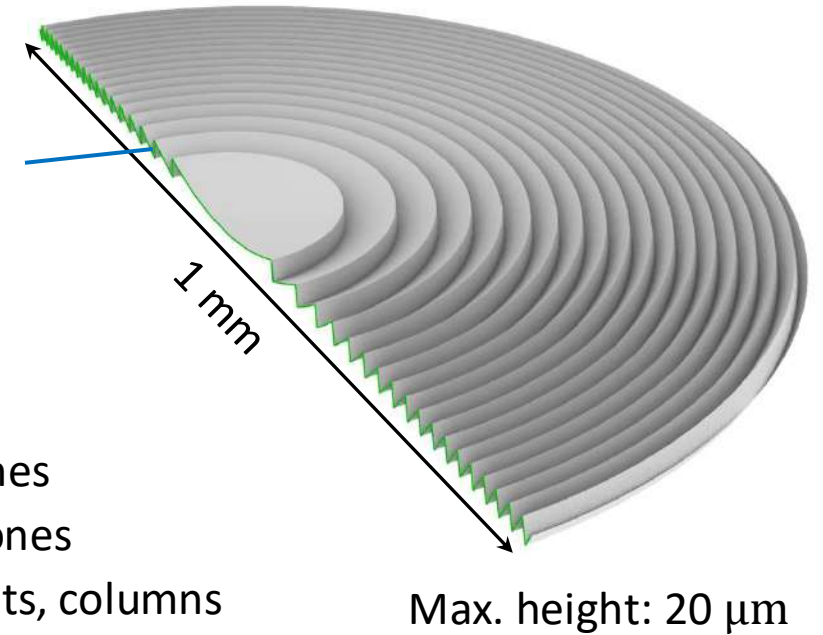
## TRAINING MODEL

Regions of different orientation and position on build platform



Concentric elements with variable radial intervals and gradients

## TEST CASE MODEL



- Base region
- Inclined planes
- Pyramids, cones
- Steps, pockets, columns
- Curved surfaces
- Hexagonal prisms
- Free-form / combined surfaces
- Column arrays

# Artificial neural network

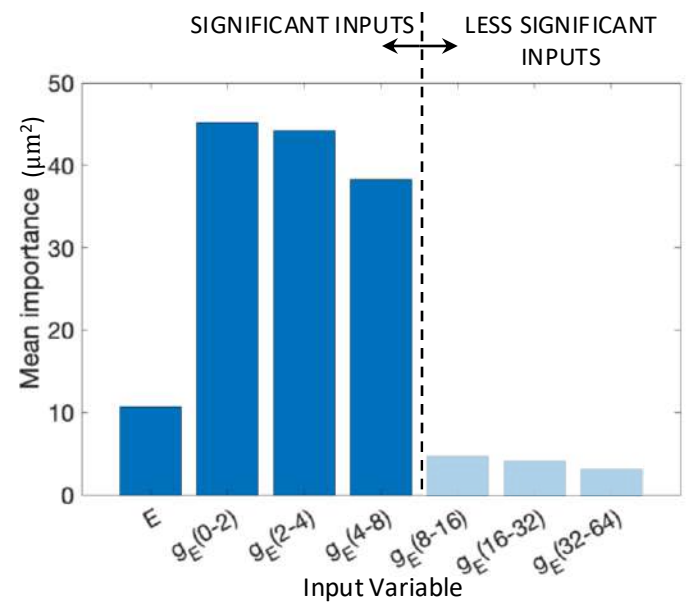
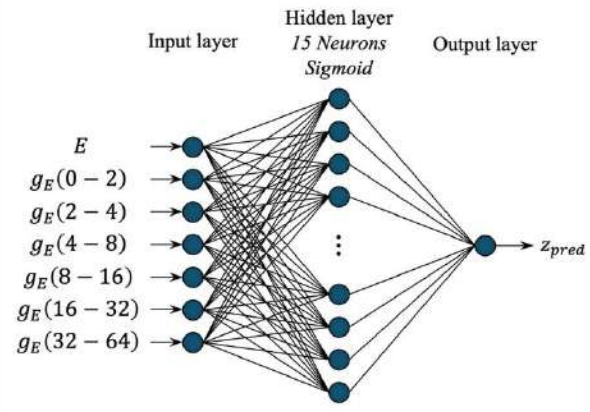
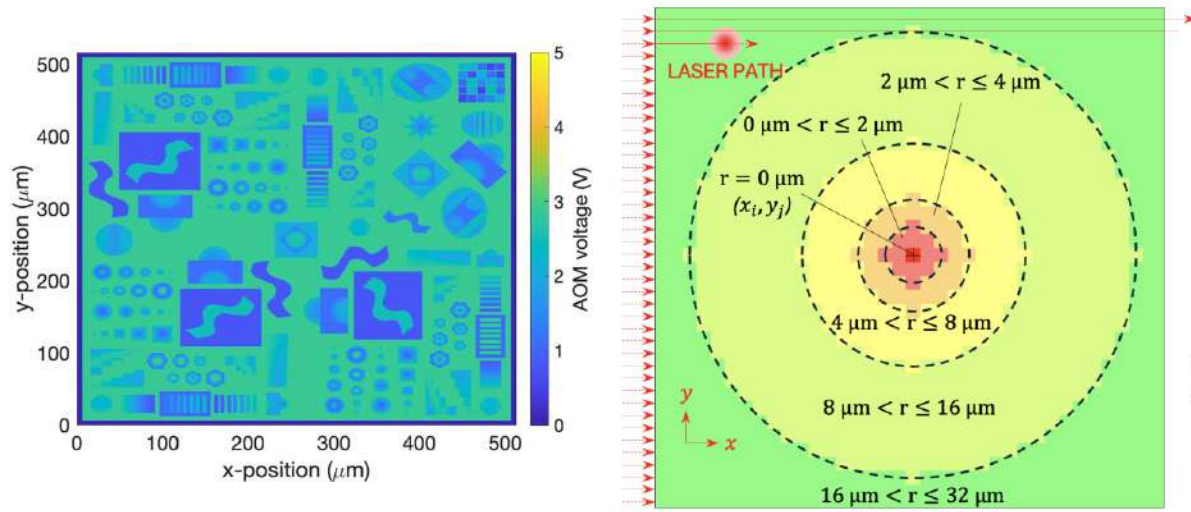
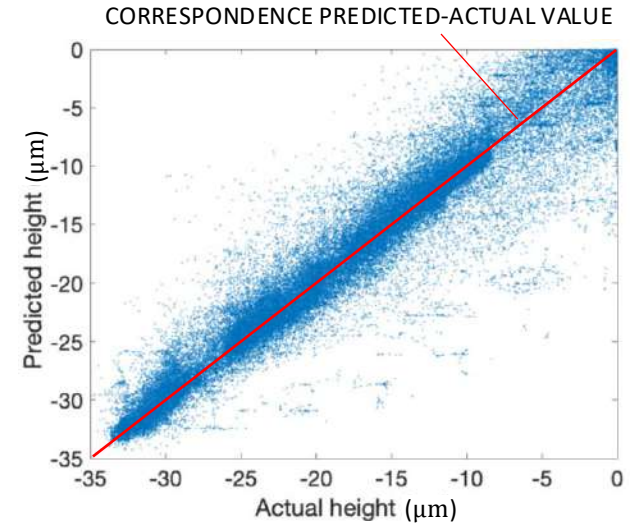


Training model employed to obtain training virtual photomask (map of AOM voltage employed to control transmitted laser power at each point) based on an experimental contrast curve. Approximately **1 million** rows of data obtained.

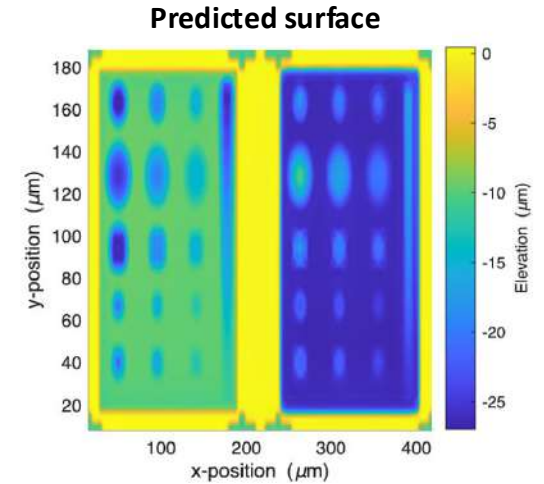
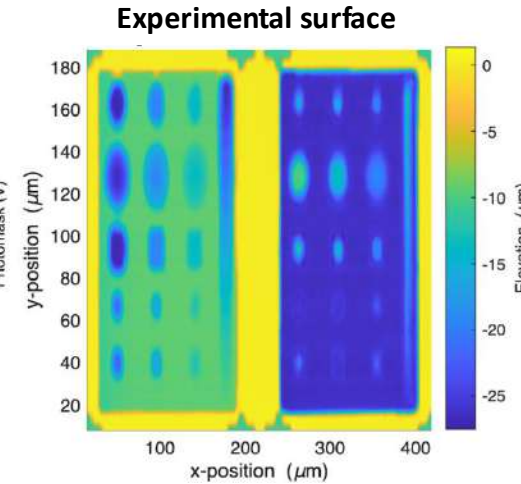
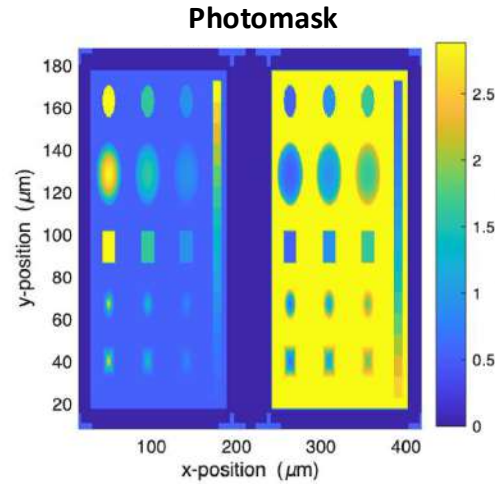
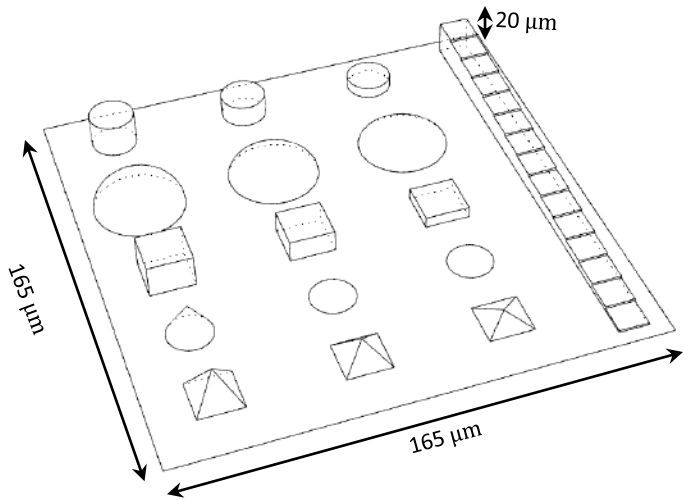
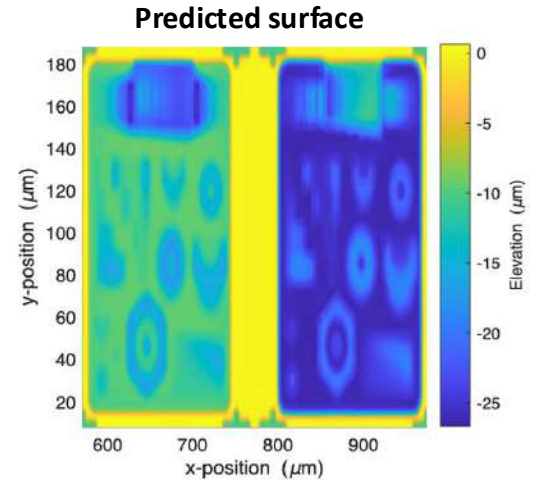
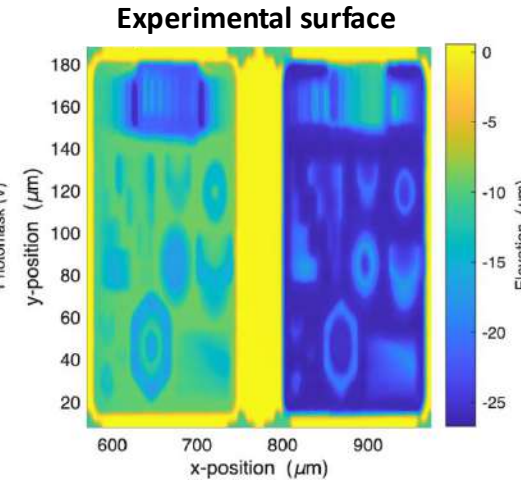
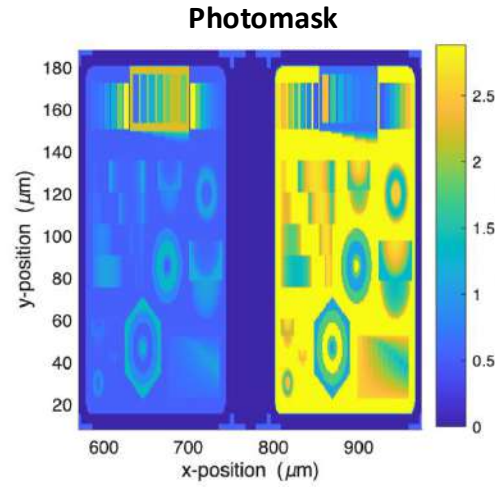
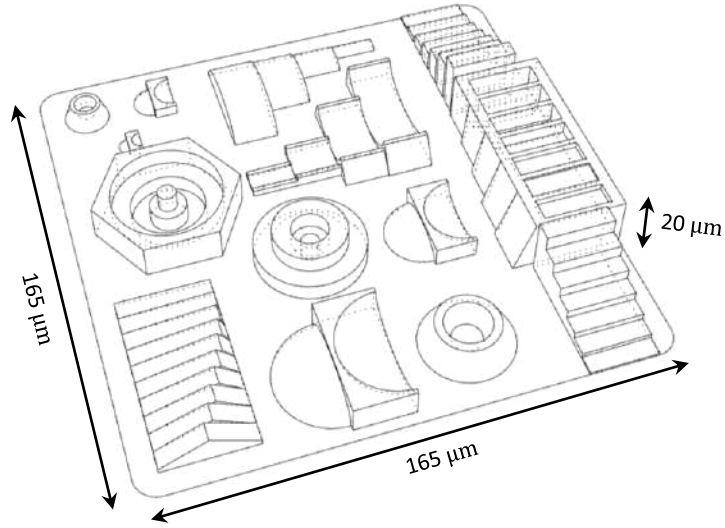
**Inputs:** Training virtual photomask,  $E$ , together with radial averages representing the radial distribution function of  $E$  at each point,  $g_E(r)$ , where  $r$  is the local radial distance from each point.

**Output:** Experimentally acquired surface topography.

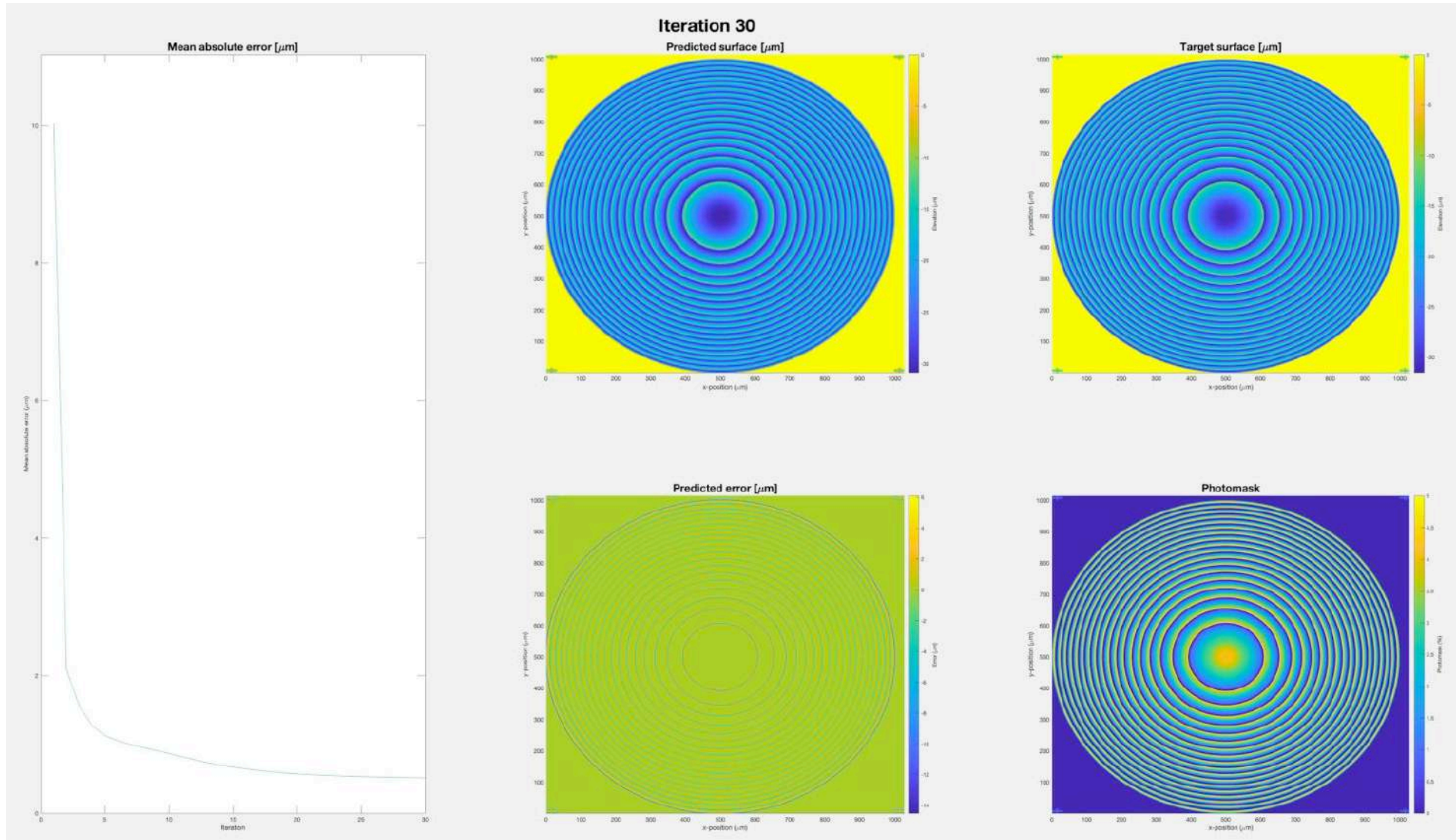
Mean squared error obtained in test set with 80%/20% partitioning of training model data into training/test sets:  $2 - 2.5 \mu\text{m}^2$ . Radial averages significant up to  $r = 8 \mu\text{m}$ .



# Artificial neural network



# Photomask optimization



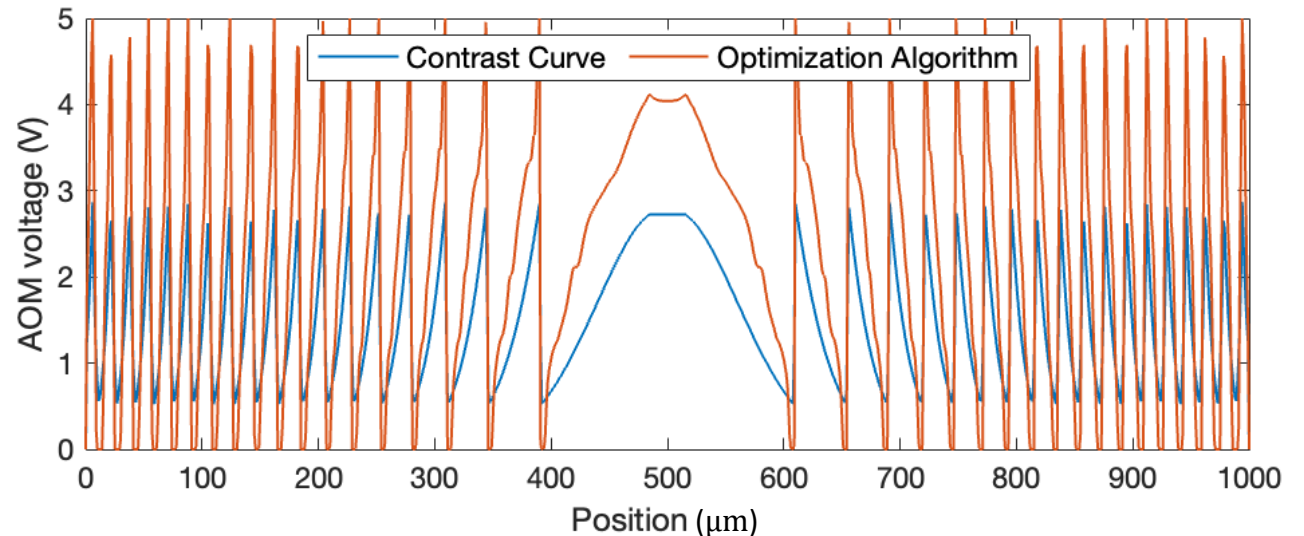
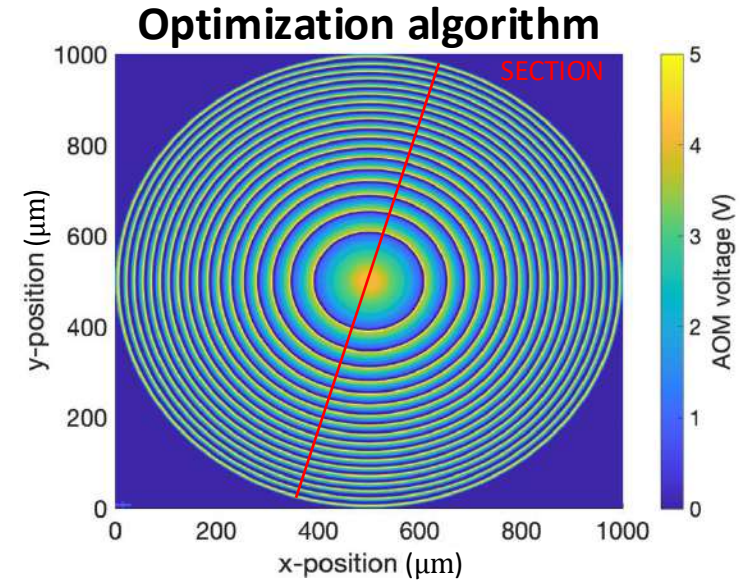
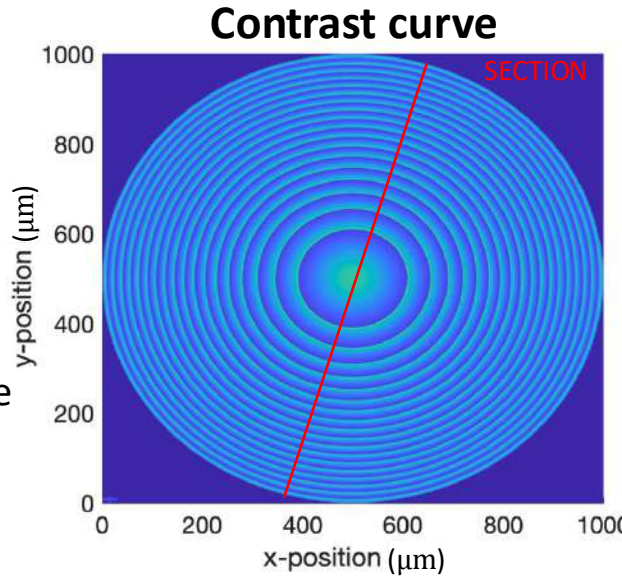
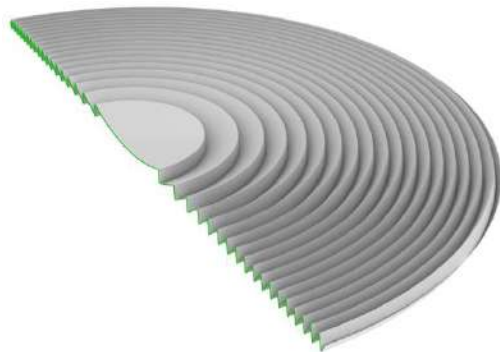
# Photomask optimization: Test case

Virtual photomask with contrast curve:

- Each point assigned value based on model elevation;
- No compensation for proximity effects or sharp edges.

Optimized photomask:

- Automatic macroscopic correction, which can be observed at the center of the optical element;
- Lower AOM values at edges of protruding features, higher values at edges of sunken features;
- Continuous compensation for proximity effects and sharp edges up to limits of the system (0-5 V).



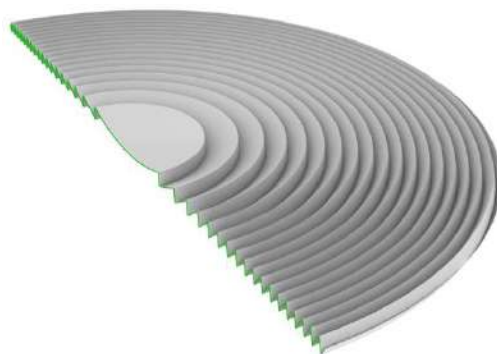
# Optimized geometry: Test case

Virtual photomask with contrast curve:

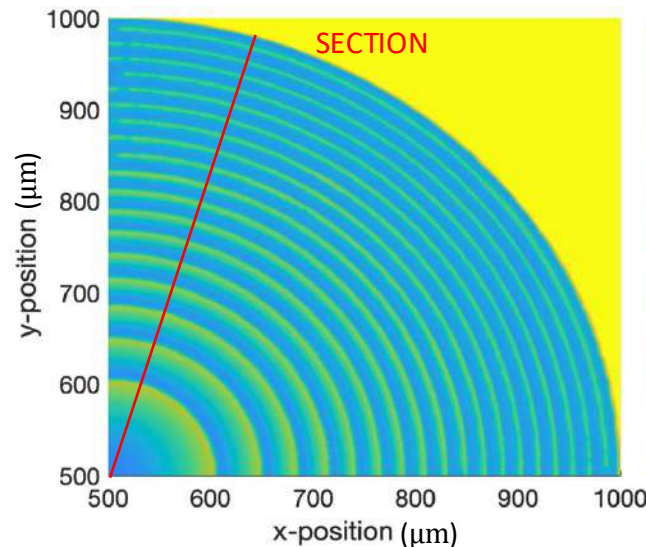
- Lower overall accuracy;
- Limited accuracy within deepest parts of valleys (error: 7-8  $\mu\text{m}$ );
- Average Euclidean distance between target and experimental surfaces: 3.6  $\mu\text{m}$ .

Optimized photomask:

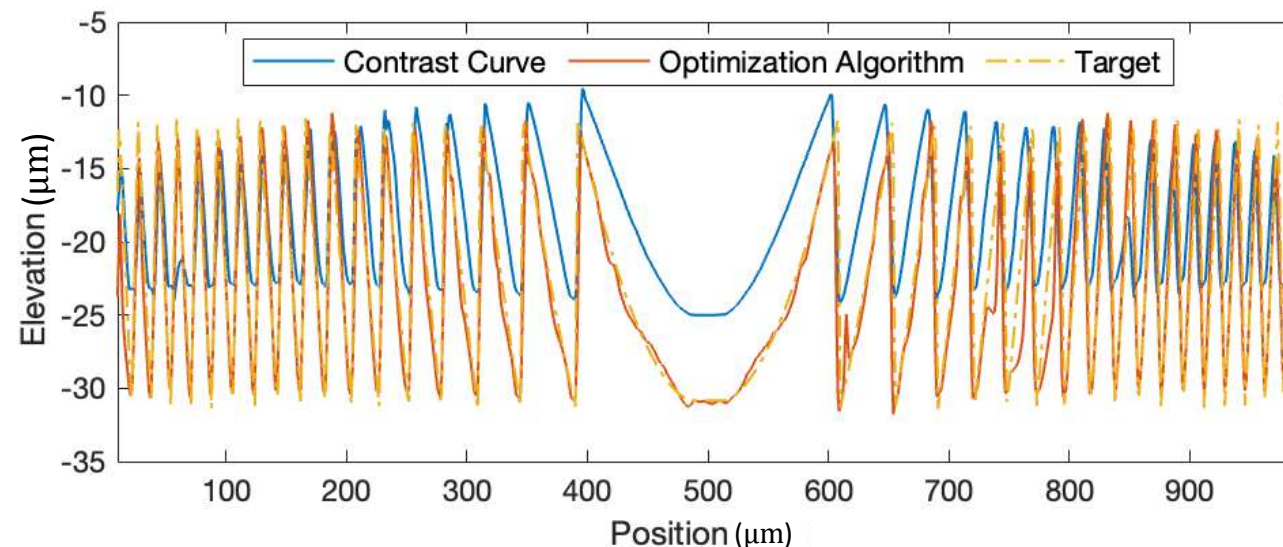
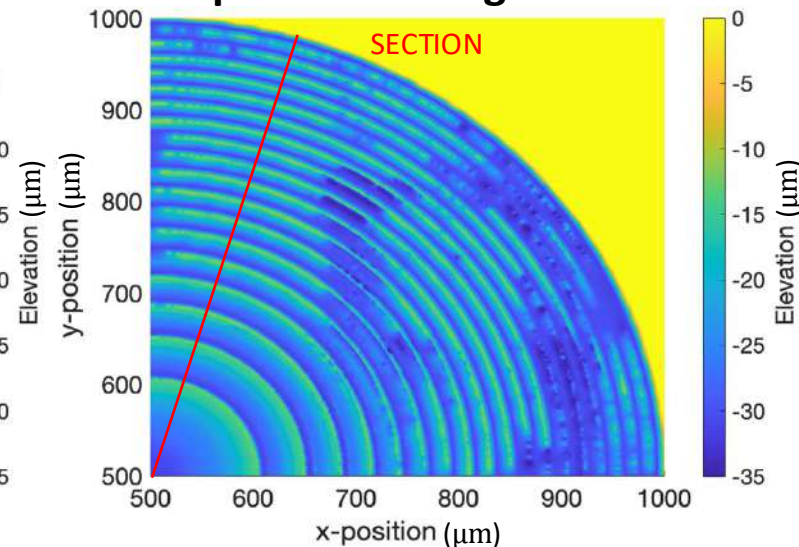
- High overall accuracy;
- Peak heights and valley depths accurate to within 1-2  $\mu\text{m}$ ;
- Many measurement artefacts due to higher aspect ratio;
- Average Euclidean distance between target and experimental surfaces: 1.0  $\mu\text{m}$ .



Contrast curve



Optimization algorithm



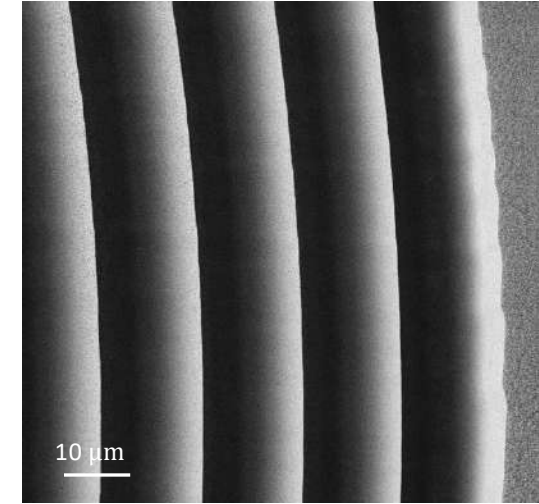
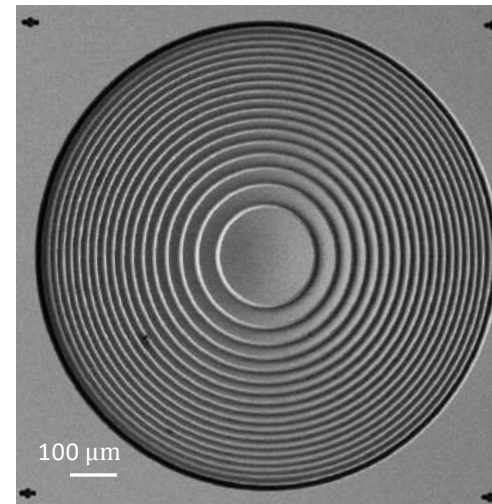
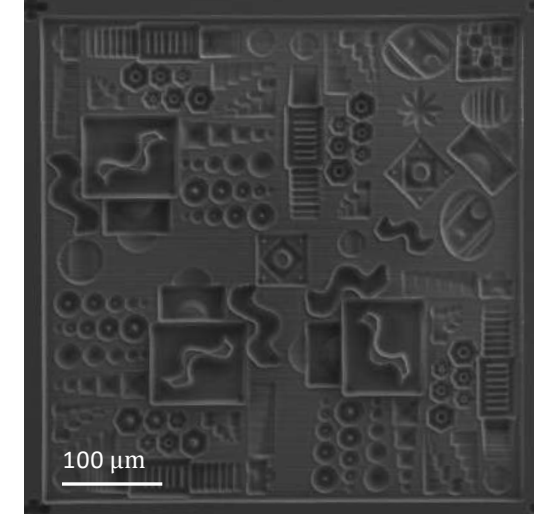
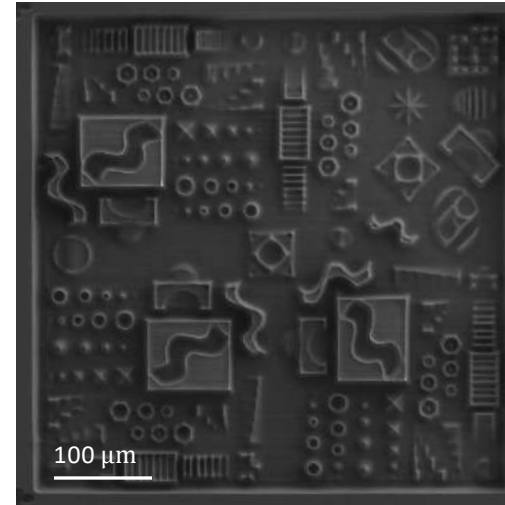
# Conclusion

Data-driven optimization has potential to **reduce time and resource requirements** for fabrication of new geometries via maskless grayscale laser lithography.

A **single** correctly setup experiment can provide a complete dataset for training machine learning models, which can then be employed in an optimization algorithm to achieve **first time right** manufacturing of new geometries **without requiring further calibration**.

## Aspects requiring attention:

- Data quality and limitations of surface acquisition techniques such as laser scanning confocal microscopy;
- Accurate representation of the entire process window, including in sub-optimal conditions;
- Extension of model to account for scanning speed, scanning direction, number of passes, photoresist, photoresist thickness, etc.



More information: <https://www.nature.com/articles/s41598-025-24652-x>

# Thank you for your attention!

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