Enabling Rapid Nanofabrication of Large-Area Metasurfaces by Innovative Algorithmic EBL Patterning

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Metalenses and metasurfaces represent a new class of flat optical components that exploit dielectric or plasmonic effects to manipulate the amplitude, phase, and polarization of light. By replacing bulky conventional optics with subwavelength-scale building blocks, metasurfaces enable compact and lightweight optical systems for applications ranging from consumer electronics and medical imaging to autonomous vehicles, AR/VR displays, sensing, and photonic communications.

Electron beam lithography (EBL) is a key technology for fabricating such structures due to its unrivaled patterning precision. However, scaling metalenses and metasurfaces to millimeter- or centimeter-scale areas remains a major challenge. Typical designs extend over several mm^2 or more and consist of hundreds of millions of uniquely sized and positioned elements—such as rectangles, circles or ellipses with feature sizes of a few hundred nanometers. Representing these irregular, non-repetitive patterns in conventional polygon-based GDSII layouts leads to extreme data volumes, often reaching hundreds of gigabytes or even terabytes, overwhelming EBL data handling, fracturing, transmission, and exposure pipelines.

To overcome these limitations, we present an innovative, lean, and highly efficient algorithmic EBL workflow that eliminates the need for generating flat GDSII design files. Instead, the metasurface or metalens pattern is described parametrically using mathematical formulas. During exposure, this algorithmic description is translated on-the-fly into the pixel stream required by the pattern generator, creating pattern data only when and where it is needed. This approach dramatically reduces data overhead, removes file size limitations, and increases throughput by up to an order of magnitude.

Using this method, a metalens with a 1 mm diameter was exposed in less than one minute. The same strategy enables the fabrication of large, irregular meta- and other surfaces with diameters up to 50 mm within practical exposure times, while maintaining full flexibility for aperiodic layouts with arbitrary and even randomized geometries or other layouts based on complex formulas. This algorithmic EBL concept opens a scalable path toward high-throughput fabrication of next-generation flat optical components.

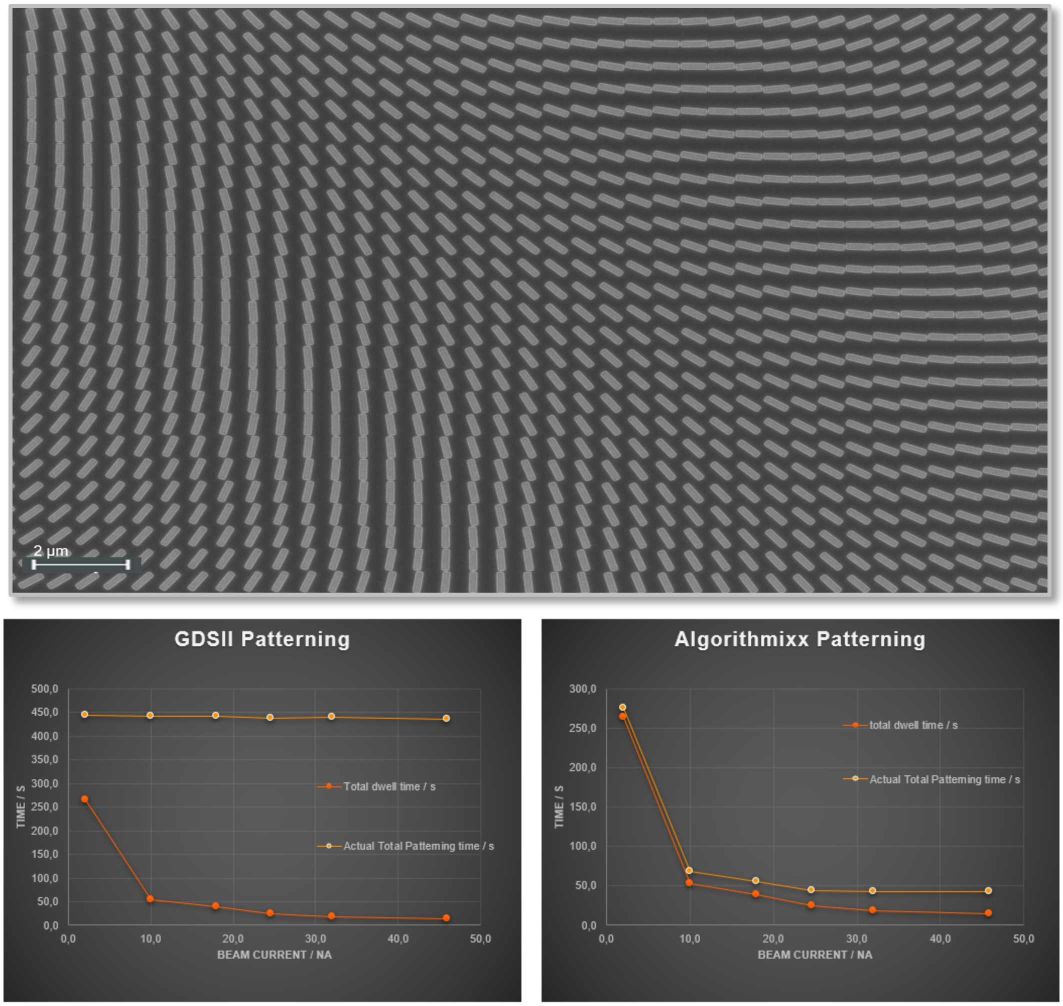

Figure 1: Metalens with 1mm² diameter, exposed with conventional GDSII based workflow as compared to new algorithmic patterning workflow. Total patterning time was reduced by an order of magnitude to less than 1min.

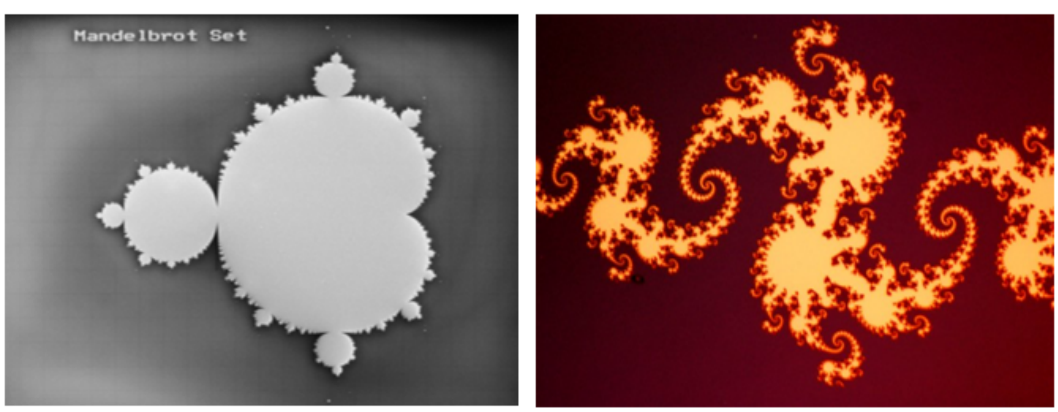

Figure 2: ”Famous” Mandelbrot and Julia sets, handled as a single shape and exposed with EBL by generating a continuous pixel stream, which is calculated on the fly using the new algorithmic patterning workflow.