Diffractive Optical Elements (DOE) and Image Printing

Diffractive optical elements (DOE) are used to shape and direct a laser beam in such a way that complex pattern (images) are displayed on a screen. The prerequisite for printing a DOE is a phase mask image from the corresponding original image (Figure 1). The phase mask must be computed in an external program before it can be imported into **DeScribe** and interpreted as a height pattern. Any phase mask creator can be used. **Nanoscribe** also offers the conversion as a service. Contact us if you would like to receive a quote.

This article covers general information about DOE creation and provides details about the **DeScribe** import wizard for images. 2D Image files are used to print diffractive optical elements (DOEs) from the corresponding phase mask images or other structures such as logos.

Phase mask creation

DOEs are based on a pattern of pixels arranged into a height pattern, which diffracts a beam of incoming laser light, such as from a laser pointer. The light passing through a material, with a thickness of d and a refractive index of n, experiences a phase shift $\Delta\phi$ as a function of the optical thickness $d \cdot n$ according to the equation:

$$\Delta\phi = \frac{2\pi}{\lambda_0} d(n_1 - 1)$$

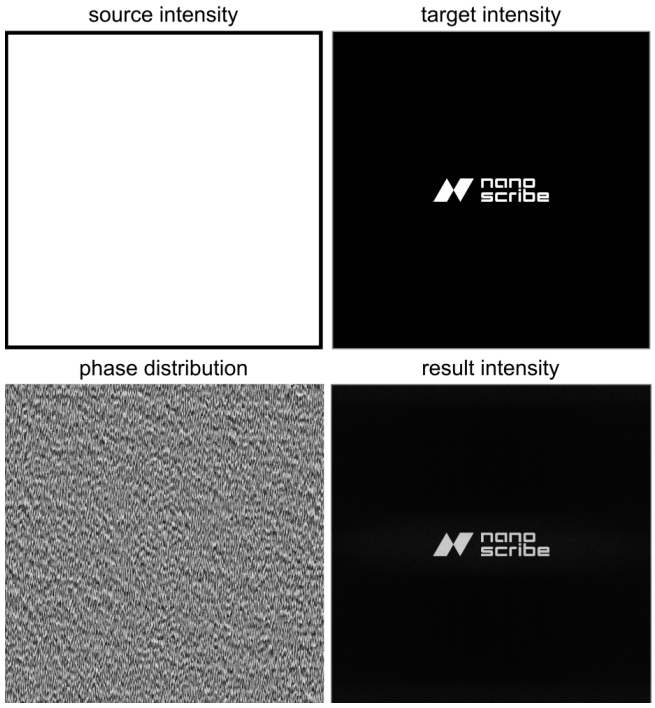


Figure 1: Phase mask computation using the Gerchberg-Saxton algorithm. Starting from a source intensity and the original image (target intensity), a phase mask (phase distribution) and its back-transformation (resultant intensity) is calculated.

Image prerequisites

The following image modifications are recommended for optimal DOE quality and sharp DOE projections from laser illumination (Figures 2 and 3):

- Convert RGB images into black and white images. Even though RGB images could be processed, the contrast of the DOE image is sharpest for pure black-and-white image templates.
- White-colored areas in the image file will appear as areas where light is present in the displayed image. Invert the image if desired.
- Only square images are allowed, with the x- and y-dimensions equal in length. Add a black square frame to the image if required.

- Transmission of the 0^{th} order diffracted laser beam cannot be avoided completely. The 0^{th} order light appears as a small light spot in the center of the displayed laser image. By moving the image within the black frame such that a white pixel of the image is in the center, this 0^{th} order spot can be masked or used as a design element (e.g. a blinking star).
- Higher-order diffraction patterns can be avoided either by using very small pixel sizes (which come at the cost of slow printing speed) or by adding additional black areas around the image.
- Images with 2000 x 2000 pixels are recommended. The standard recipe for DOE creation sets the pixel size of the printed DOE as 2 x 2 μm^2. The resulting printed object will be 4 x 4 mm^2, which is a similar size to the beam diameter of a laser pointer.

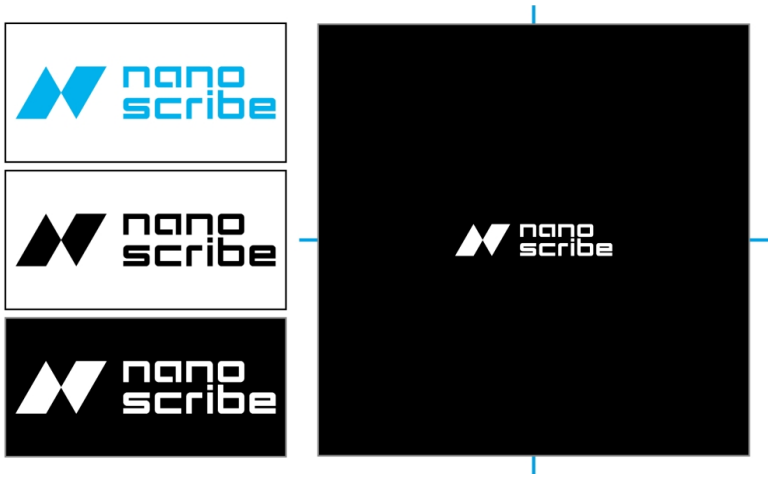


Figure 2: Recommended RGB image modifications prior to phase mask calculation.

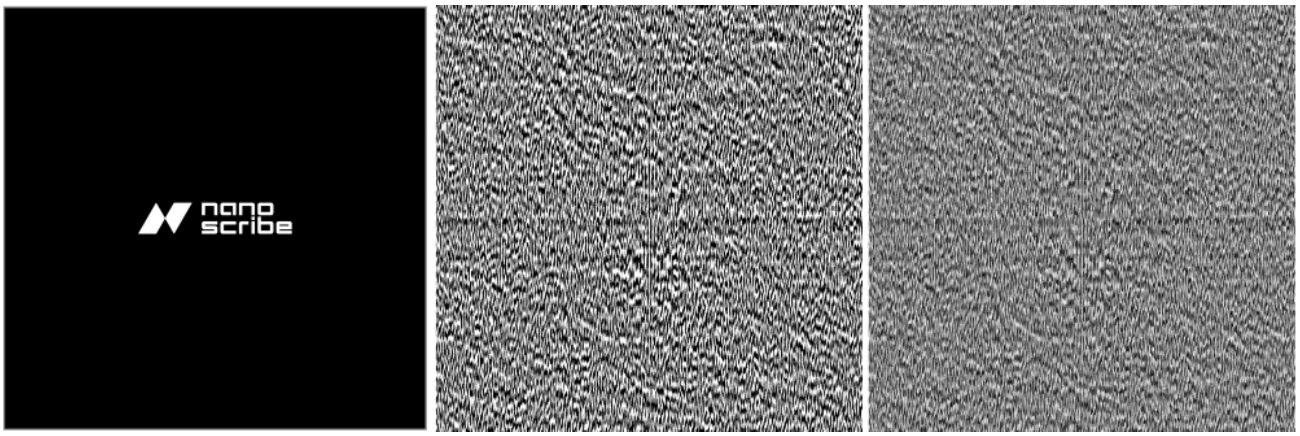


Figure 3: Image conversion: Image to be converted (left) and phase masks with 2 (middle) and 8 (right) phase steps respectively.

Print set

The **DeScribe** import wizard provides a standard recipe to print DOEs from a phase mask. The recipe is designed for DiLL using the 63x objective and silanized fused-silica substrates (3D SF

DiLL). DOEs printed with this standard recipe are tailored to an illumination wavelength of 640 nm. Other user-defined recipes for different illumination wavelengths can also be created and used.

DeScribe image import wizard

The image import is integrated within **DeScribe** and appears similar to the STL file import. The user interface adapts not only to the image import but also to two different processing types, which are explained below:

- Height field type | Discrete is intended for printing DOEs based on phase masks (Figure 1).
- Height field type | Continuous is mainly used for printing logos from 2D images (Figure 7).

Several image formats are supported, namely **.bmp*, **.png*, **.tif*, **.tiff*, **.jpg* and **.jpeg* files. Lossless compressed image formats (*.bmp, *.png, *.tif, *.tiff) are recommended to minimize compression artifacts. Supported pixel formats are Bgr24, Bgra32, Rgb48, Rgba64, Gray8 and Gray16. The import wizard interprets either the grayscale value (up to 16 bit) or the pixel brightness (for color images) as the z-value in **DeScribe**. The allowed image file size is limited only by the memory of the computer.

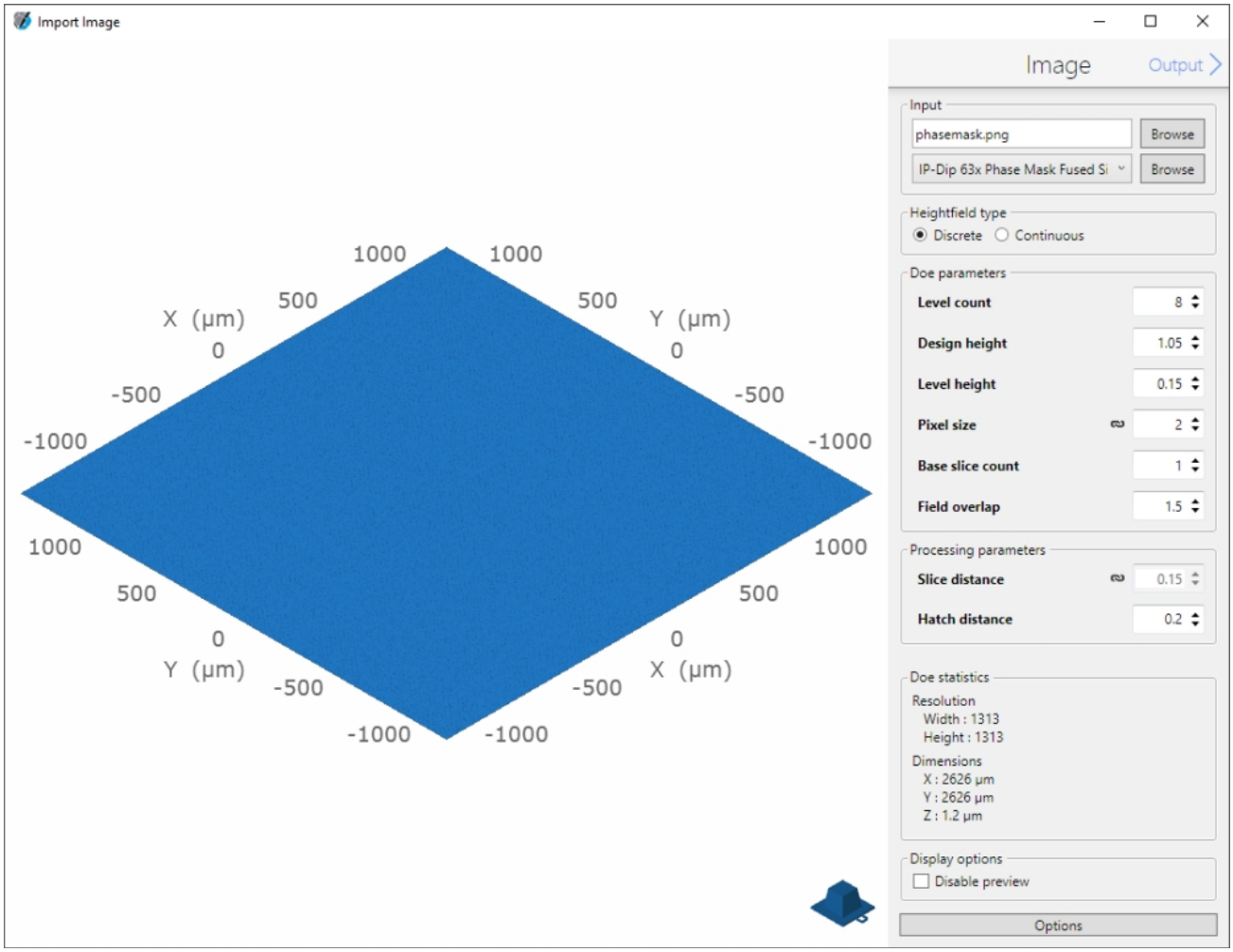


Figure 4: Import wizard for DOE printing Height field type Discrete.

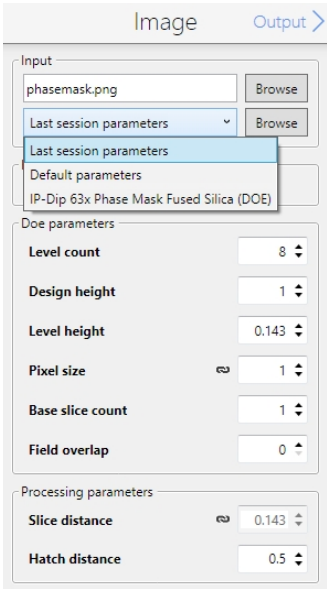


Figure 5: A recipe for the creation of 640 nm DOEs is available if Height field type Discrete *is selected.*

Height field type: discrete

Once the phase mask image from a image is created and is loaded into **DeScribe**, a limited number of DOE parameters are available. These can be set manually or are automatically defined by the selected recipe (Figures 4 and 5).

- Level count sets the number of discrete height values (Figures 4 and 6). Gray values imported from the phase mask will be binned correspondingly. For example, if the imported phase mask has 255 gray values, Level count must be set to 256 to represent all gray levels including the base layer (Figure 6-1). Setting Level count to 3 results in appropriate binning of several gray values (Figure 6-2). The level also determines the quality of the DOE. If too few levels are used, a centrosymmetric far-field pattern can result, whereas more levels break the symmetry as typically is desired. Level count is automatically set based on the input image.
- Design height is the result of Level count multiplied by Level height (Figure 6-3). Design height must be adjusted to the wavelength of the laser according to the equation:

$$\Delta\phi = \frac{2\pi}{\lambda} d(n-1)$$

with $\Delta\phi \stackrel{!}{=} 2\pi$ for constructive interference. Hence, Design height results from:

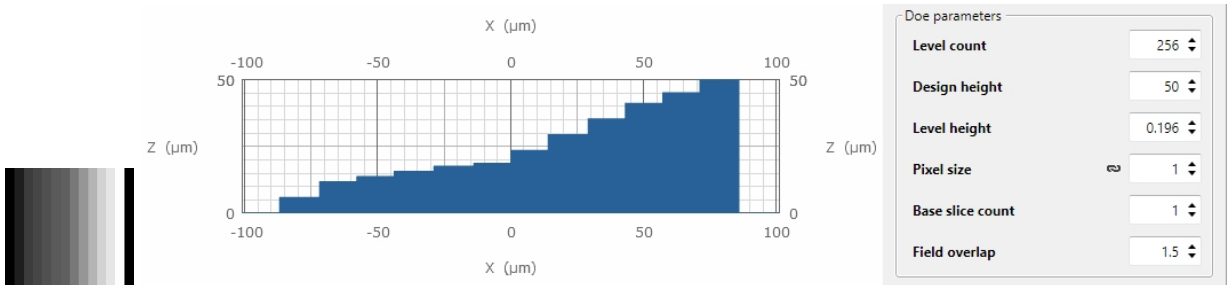
$$d = \frac{\lambda_0}{n_1 - 1}$$

and Level height from:

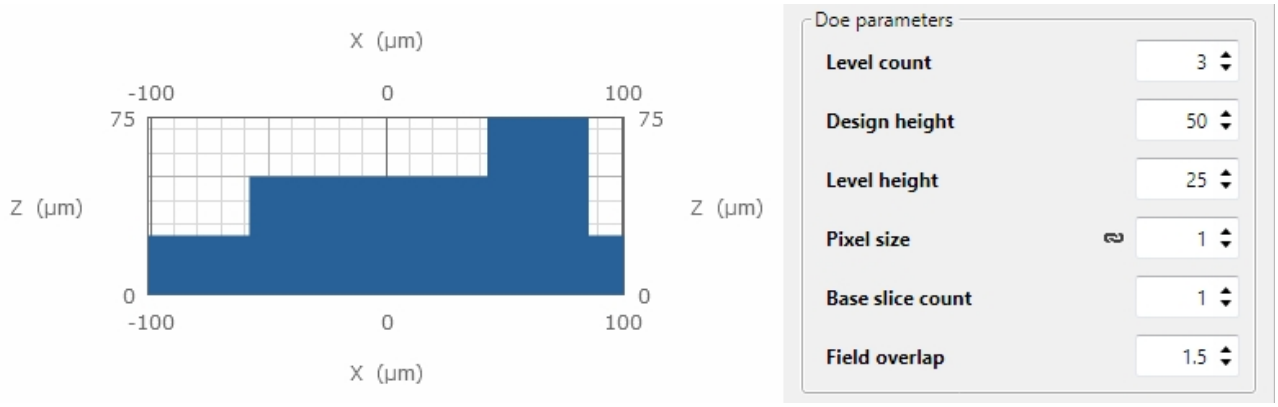
$$d_{k-1} = \frac{d}{k-1}$$

The size of the imported phase mask can be increased by changing Pixel size (in µm). Base slice count defines the number of base slices that will be added before the phase mask is printed (Figure 6-4).

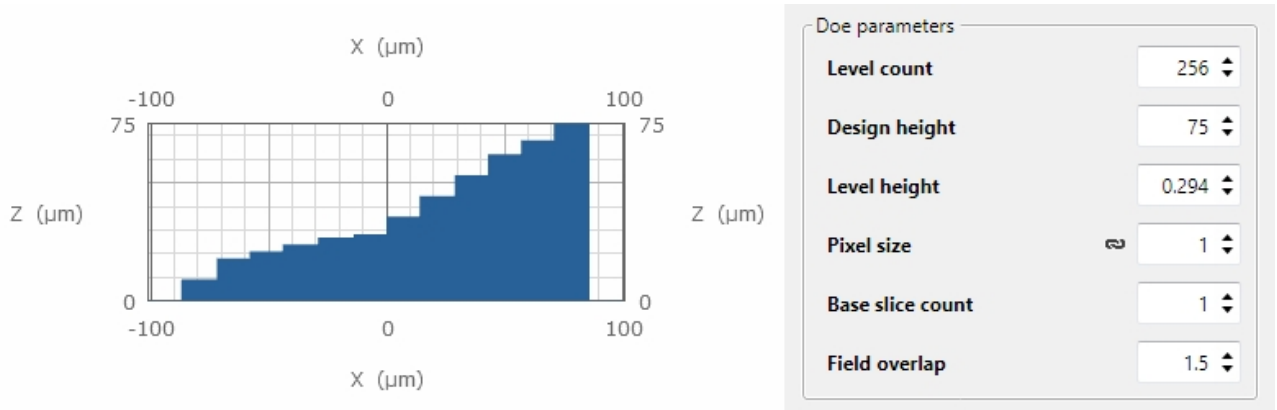
- The Processing parameters Slice distance and Hatch distance control printing properties (Figure 6-5). Each level of the DOE can be printed in multiple slices and each pixel in multiple lines. However, Slice distance must not exceed Level height and Hatch distance must not exceed Pixel size to correctly represent the imported phase mask in the printed profile. A Pixel size of 2 µm is standard. Smaller Pixel size values increase the edge portion of the level steps in comparison to the step plateau, which reduces the print quality. The overall print field should be a multiple of Pixel size for best print quality.
- Field overlap is connected to the Splitting feature of the proceeding Output tab and determines the overlap of each print field.



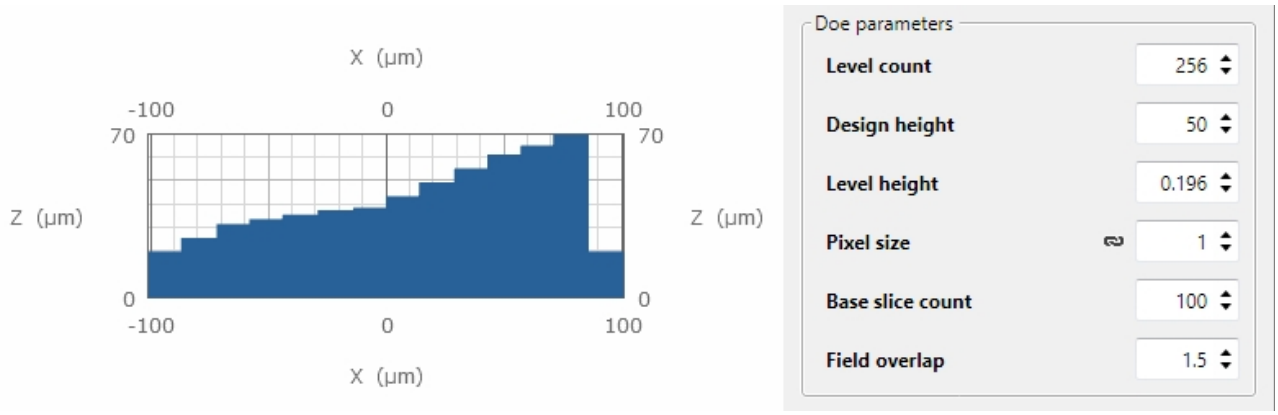
6.1: Image imported into **DeScribe** *with a* Level count *of 256.*



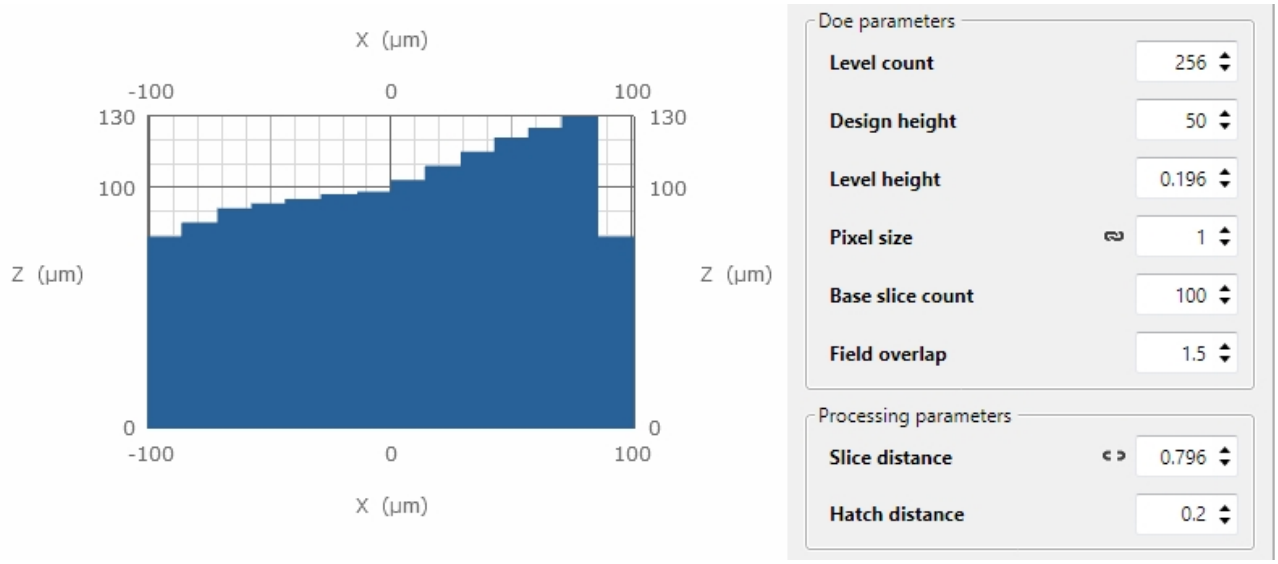
6.2: Level count *set to 3.*



6.3: Design height *increased and* Level count *set to 256.*



6.4: Base slice count *is increased to 100.*



6.5: Slice distance *is chosen independently of* Level height.

Figure 6: Changing DOE parameters for Height field type Discrete *in the image import wizard.*

The import wizard Output tab sets the splitting field dimensions and provides an option to repeat the DOE multiple times in a tiled array. The output folder and file name can be chosen (Figure 7). The minimum size of the DOE depends on the diameter of the laser beam used to illuminate the DOE. The tiling feature can be used to repeat the DOE pattern to match the laser beam diameter. That being said, consider increasing Pixel size rather than creating an array. Avoid stitching seams located at central tiles by using odd numbers for the array size. Seams can be masked using Field overlap in the Image tab.

Figure 8 displays a processed DOE preview and a close-up image of the structure. DOEs printed on a transparent substrate can be used in combination with a red (640 nm) laser to display the target image on a screen (Figure 9).

> The output data from Height field type Discrete image import is binary (**.gwlb*) and so **NanoWrite** 1.8 or later is required.

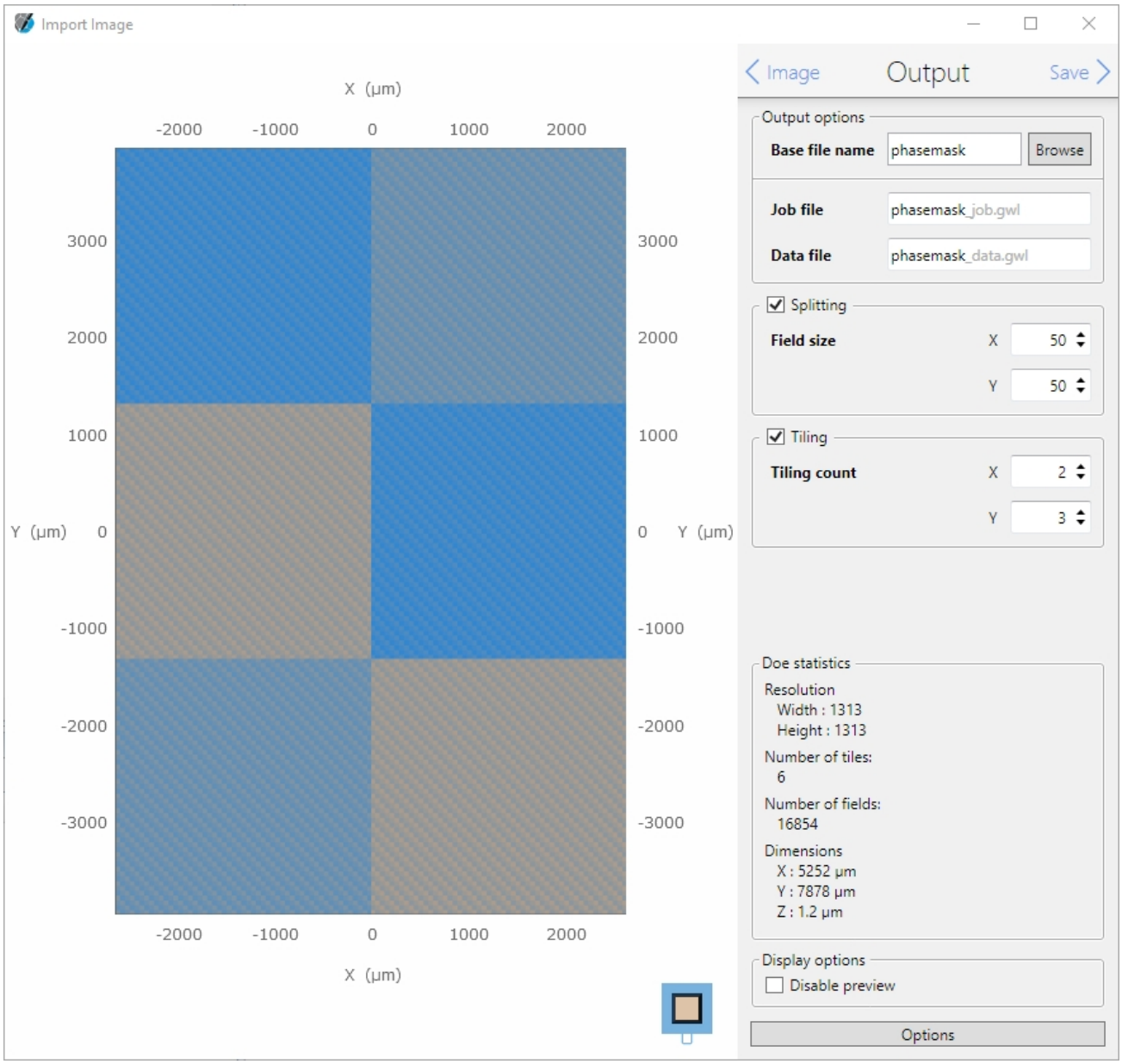


Figure 7: Image import wizard Output *for* Height field type Discrete*. The large squares indicate* Tiling counts *and the small squares represent the* Splitting Field *size.*

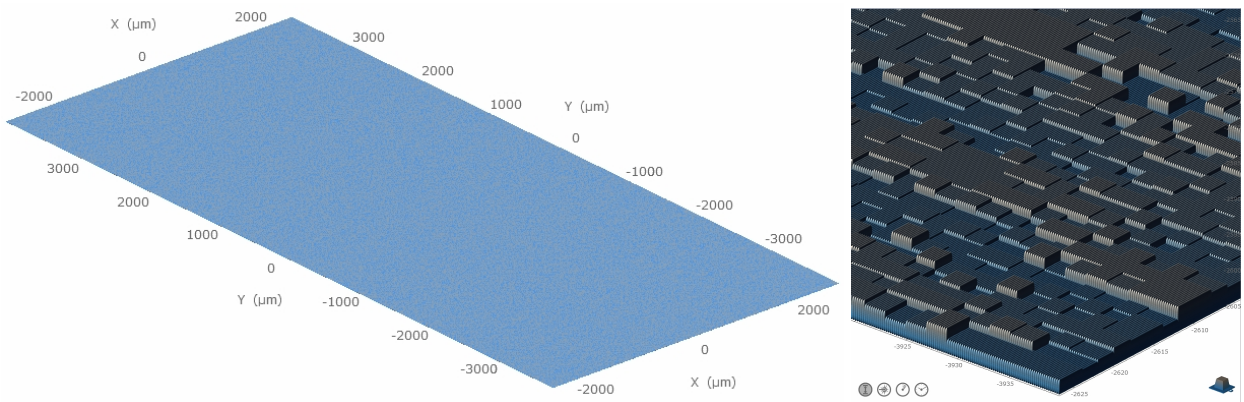


Figure 8: Processed DOE preview using **DeScribe** *2.5 and a close-up image displaying height differences of*

the DOE pixel for Height field type Discrete.

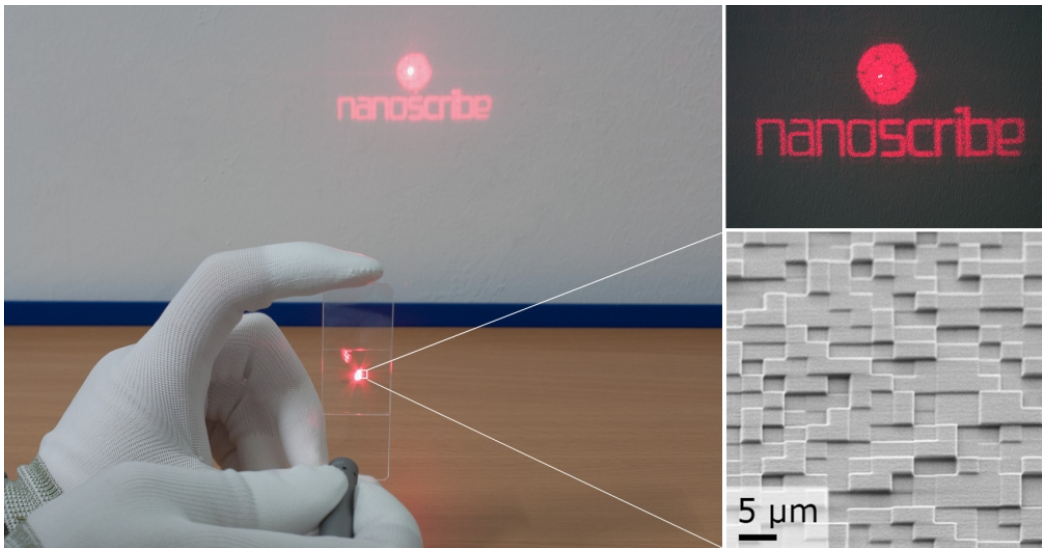


Figure 9: **Nanoscribe** *logo (older version), using a DOE printed on a transparent substrate that is illuminated with a red (640 nm) laser.*

Height field type: continuous (for printing logos)

The import wizard user interface adapts if Height field type Continuous is selected (Figure 10). Instead of the Output tab (used for Height field type Discrete), an additional Hatching tab is available, which allows to set the Hatching and Slicing distance (Figure 11). Note that this workflow does not require square image files.

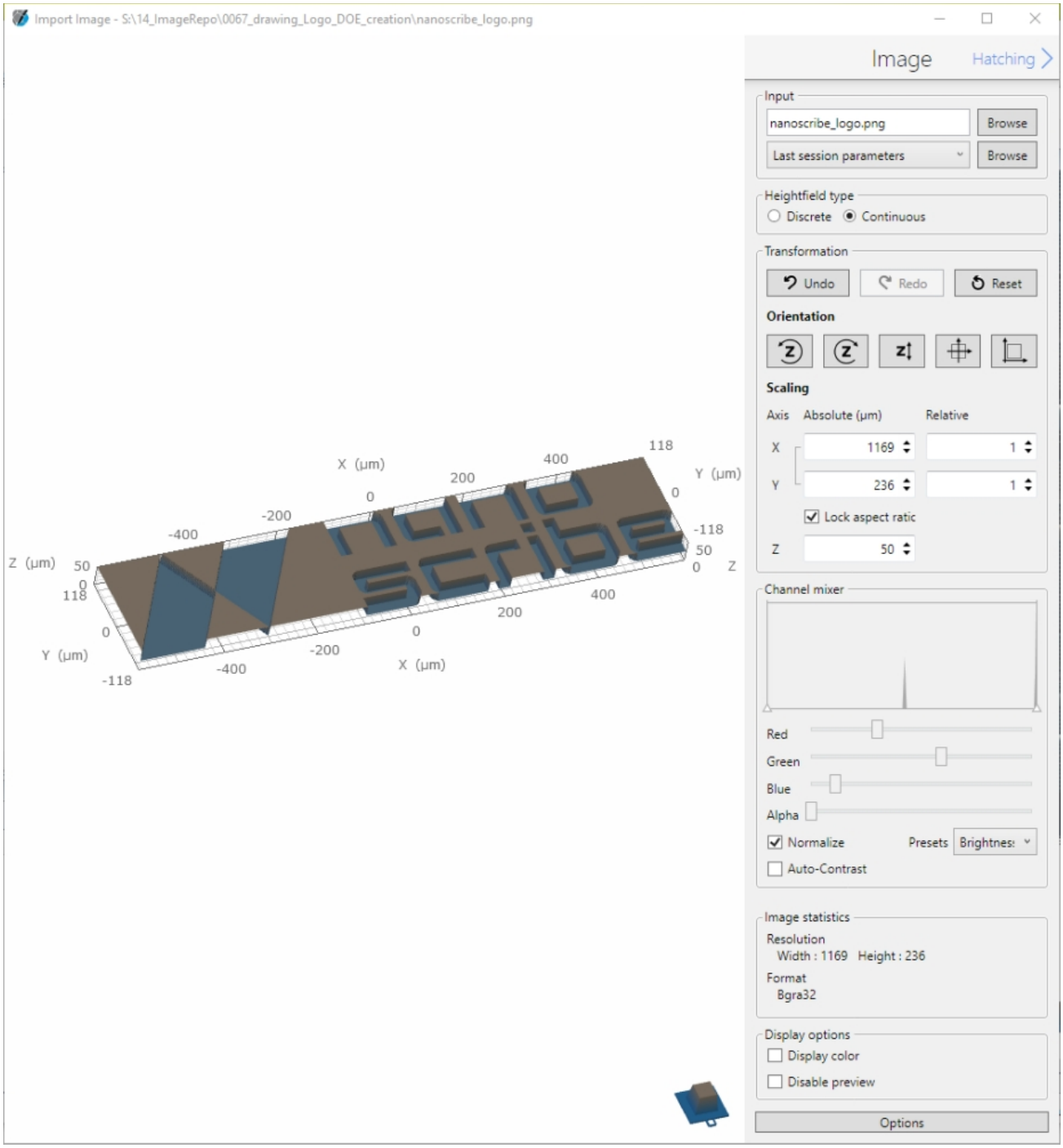


Figure 10: Image import wizard for Height field type *Continuous* *to print logos or similar 2D structures.*

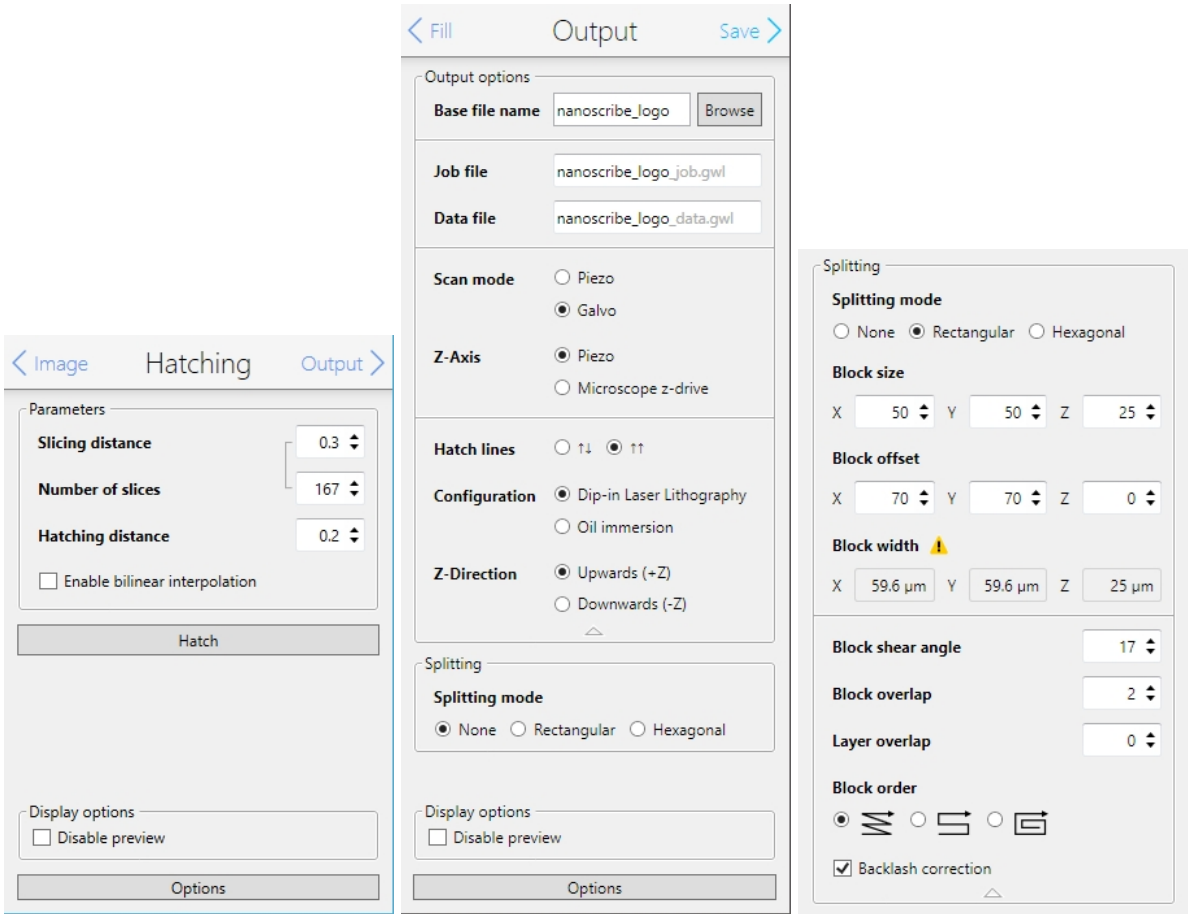
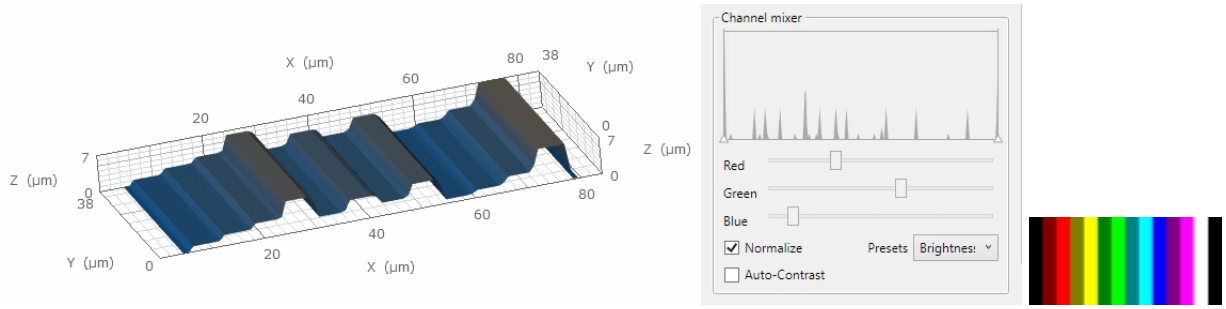


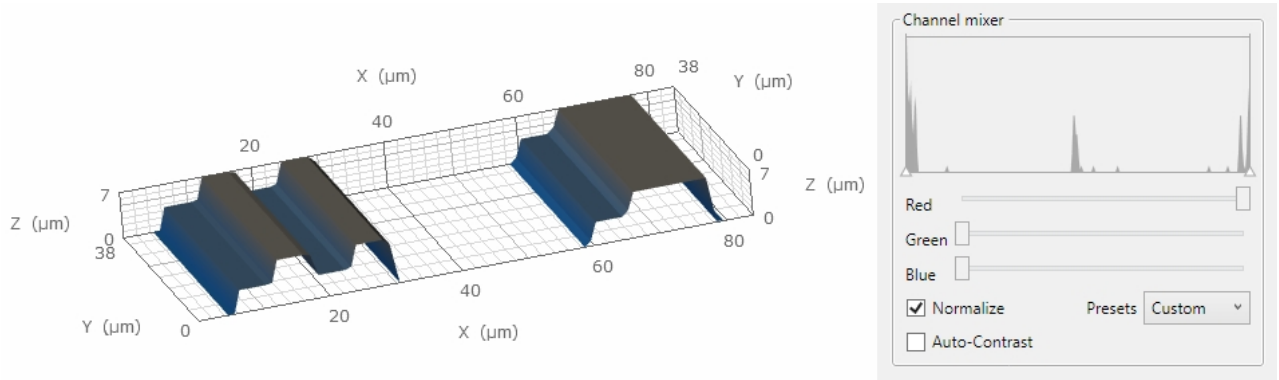
Figure 11: Import wizard for Height field type | Continuous *with* Hatching *(left) and* Output *(middle: no splitting; right:* Splitting mode | hexagonal*) tabs displayed.*

The import wizard Image tab contains options for Orientation and Scaling transformation, similar to the STL file import workflow (Figure 10). The Channel mixer frame provides value sliders to adjust the colors of the imported image. These will determine how the image height profile is interpreted (Figure 12).

> A negative Scaling value mirrors the model along the corresponding axis.



12.1: Image imported into **DeScribe** *using* Height field type Continuous.



12.2: The preset *was changed to* Red.

Figure 12: Import wizard for Height field type Continuous *demonstrating the influence of channel mixer settings on the imported image.*

The Hatching and Slicing distance must be adjusted according to the imported image and the chosen Channel mixer settings for best results. The minimum Slicing distance must be smaller or equal to the smallest height difference of the imported image (for example if brightness is translated into z-values) and Hatching distance must match the pixel size of the imported image to represent all details of the image in the printed structure.

The import wizard Output tab defines certain printing parameters such as Scan mode and Splitting settings, similar to those known for STL file import (Figure 11). A preview of the structure is given in Figure 13.

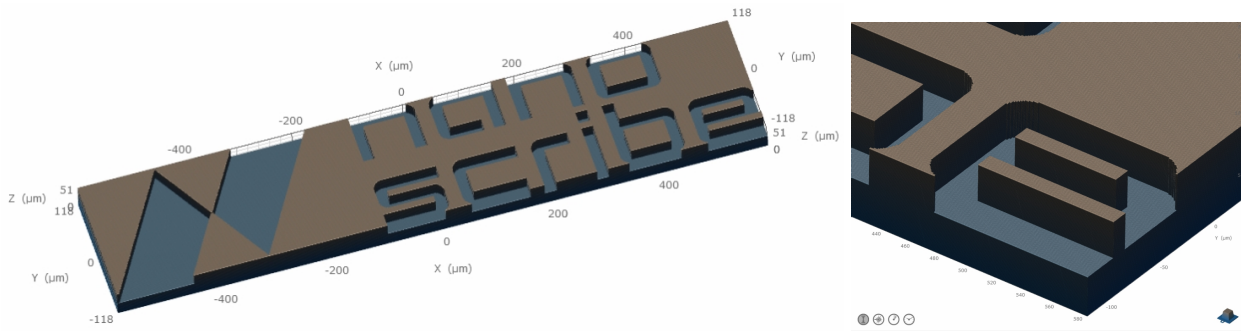


Figure 13: **DeScribe** *preview of the* **Nanoscribe** *logo imported and processed with the image import wizard using* Height field type Continuous. *The close-up image shows height differences of the logo and a base layer.*

Publication references

The following publications are related to diffractive optical elements:

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