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GDOESII: Software for design of diffractive optical elements and phase mask conversion to GDSII lithography files

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ABSTRACT

We develop an open source software "*GDoeSII*" for the simulation of Fresnel (near field) and Fraunhofer (far field) diffraction integrals of diffractive optical elements (DOE). It can compute the intensity distributions at a desired plane from the DOE. This software can also convert the phase profiles of the DOEs from standard image formats such as JPG and PNG to lithography graphic format GDSII for fabrication purposes. The conversion algorithm used in this program groups adjacent same-valued pixels and creates a single cell rather than creating a cell for each and every pixel in the image file. This results in a faster and smaller output GDSII file size. Conversion to the multi-layer GDSII format is also possible for grayscale lithography. We show, as an example, the simulation, GDSII conversion, fabrication and experimental results for the case of an Airy beam generator. *GDoeSII* offers a complete platform for researchers working in diffractive optics from simulations to lithography file preparation.

Code metadata

Current code version	v1
Permanent link to code/repository used for this code version	https://github.com/ElsevierSoftwareX/SOFTX_2018_239
Legal Code License	CC by NC 3.0
Code versioning system used	None
Software code languages, tools, and services used	Python 2.7
Compilation requirements, operating environments & dependencies	Windows OS (7 and above)
If available Link to developer documentation/manual	
Support email for questions	gdoesii@gmail.com

Software metadata

Current software version	1.0
Permanent link to executables of this version	www.gdoesii.com
Legal Software License	CC by NC 3.0
Computing platforms/Operating Systems	Windows OS (7 and above)
Installation requirements & dependencies	None
If available, link to user manual - if formally published include a reference to the publication in the reference list	NA
Support email for questions	gdoesii@gmail.com

1. Motivation and significance

Diffractive optical elements (DOE) are thin phase or amplitude elements that operate by means of diffraction to produce arbitrary

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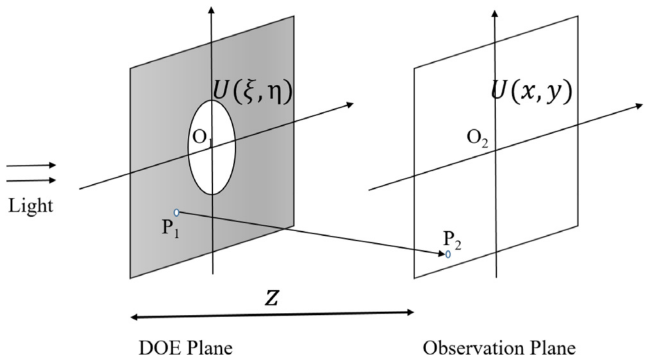

Fig. 1. Geometry of the planes for scalar diffraction theory.

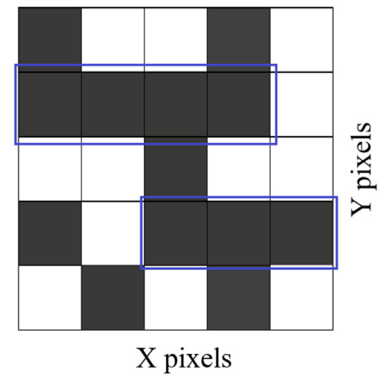

Fig. 3. Grouping of same valued pixels in a row.

distributions of light. Some examples of DOEs include diffraction gratings, Fresnel zone lenses [1], and diffractive axicons [2] and so on. DOEs are extensively used as beam shaping elements, lenses and other essential optical components. The typical design flow of a DOE is as follows: (1) Calculation of DOE phase profile, using techniques such as the G-S algorithm [3], simplified mesh technique [4], modulo 2π conversion of refractive elements or analytic equations [5]; (2) Simulating the optical fields using scalar diffraction equations; (3) Fabrication using lithography techniques followed by experimental verification.

In this paper we present *GDoeSII*, an all-in-one software with graphical user interface, which allows users to perform scalar diffraction simulations and then convert the phase profiles from standard image formats such as JPG and PNG to GDSII format for further lithography process. The following sections explain the implementation details of the two main modules of the software which are: 1. DOE module, 2. GDSII conversion module. An example is presented where the simulation and experimental results are shown for the case of Airy beam generation.

2. Software description

2.1. Diffractive optics module

In this section, we discuss the theoretical background behind the DOE simulator module. The geometry of the problem is shown in Fig. 1. We used Fresnel and Fraunhofer scalar diffraction integrals to compute the intensity of the field distribution at a desired plane from the DOE. The software uses the Fresnel (*near field*) diffraction integral Eq. (1) to compute the complex field $U(x, y, z)$ at a distance z from the DOE plane.

$$U(x, y, z) = \frac{e^{ikz}}{j\lambda z} e^{j\frac{k}{2z}(x^2+y^2)} \iint \{U(\xi, \eta) e^{j\frac{k}{2z}(\xi^2+\eta^2)}\} e^{-j\frac{2\pi}{\lambda z}(x\xi+y\eta)} d\xi d\eta, \tag{1}$$

where x, y are the coordinates in the observation plane and ξ, η are the coordinates in the DOE plane, k is the wave vector and λ is the wavelength of the light. A simplified version of Eq. (1), also known

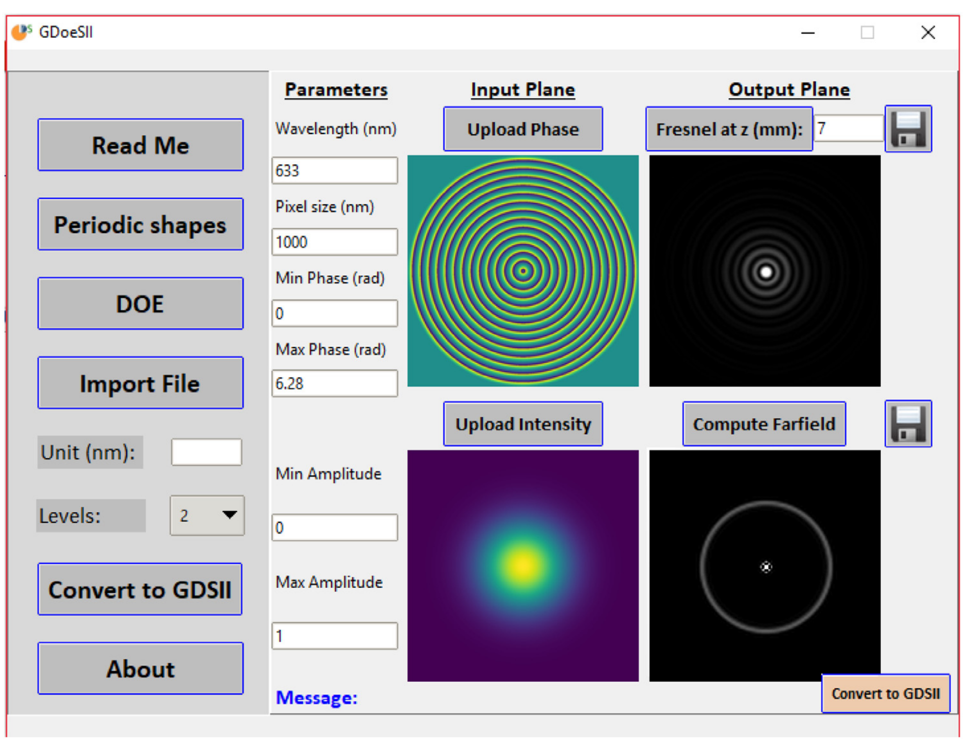

Fig. 2. Diffractive optics simulation module.

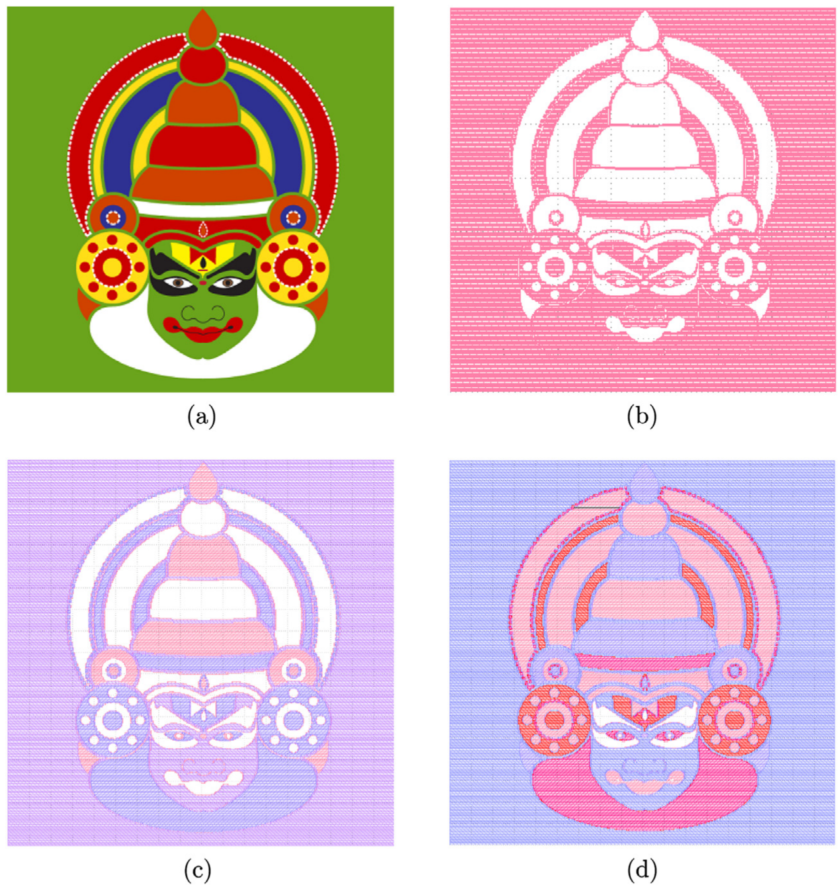

Fig. 4. (a) Original image, Converted GDSII files (b) 2 level (c) 4 level (d) 8 levels.

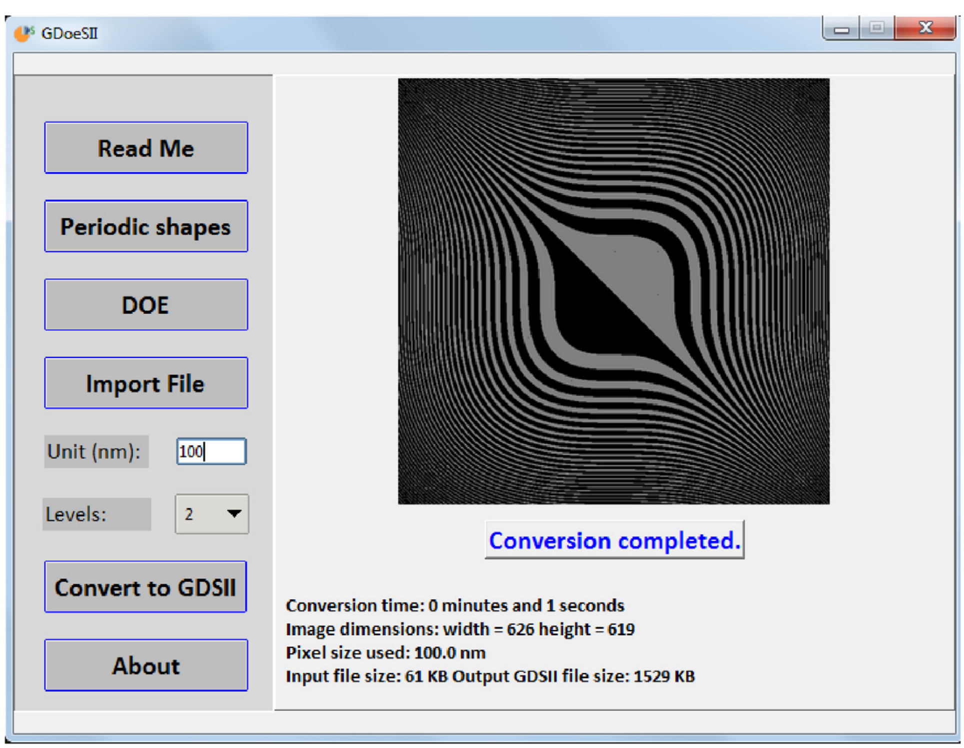

Fig. 5. GDSII conversion module.

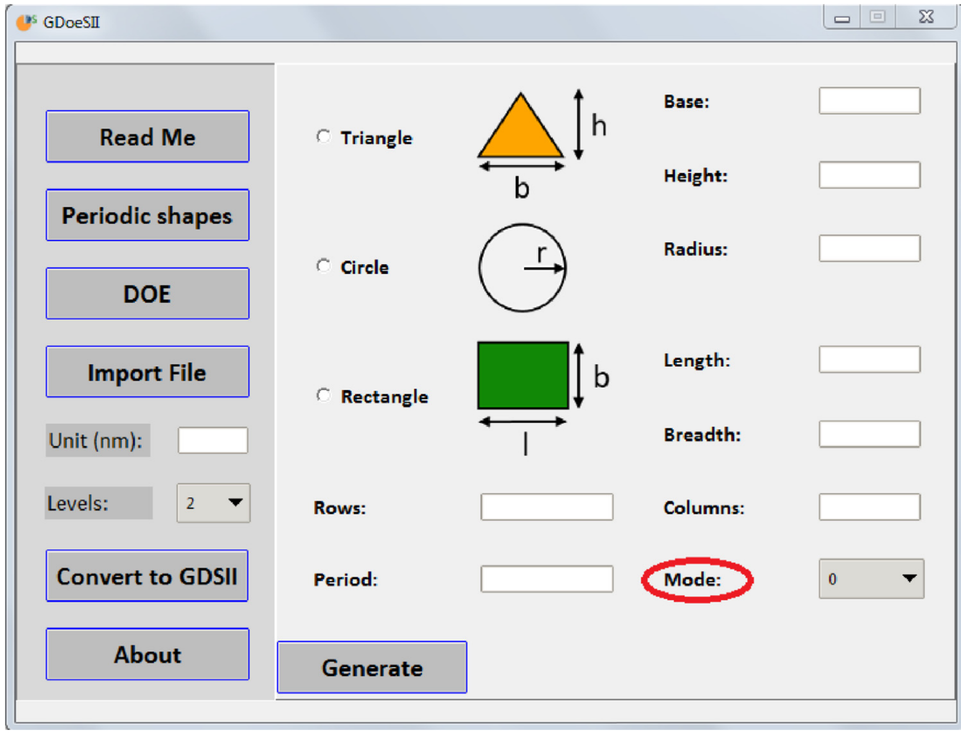

Fig. 6. Periodic arrays of basic structures can be created using this module.

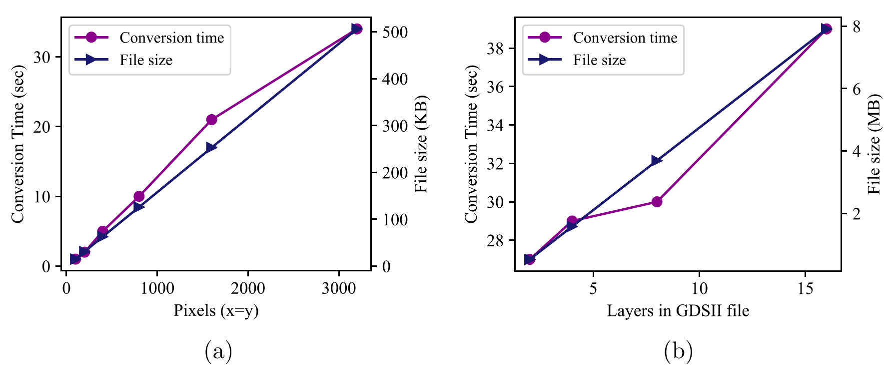

Fig. 7. GDS file conversion time and output file size (a) for different image sizes (b) for same image but different number of layers in output GDS file.

as Fraunhofer diffraction (*far field*) integral given in Eq. (2) is used to compute the complex field in the far field.

$$U(x,y) = \frac{e^{jkz}e^{j\frac{k}{2z}(x^2+y^2)}}{j\lambda z}\iint U(\xi,\eta)e^{-j\frac{2\pi}{\lambda z}(x\xi+y\eta)}d\xi\, d\eta \qquad (2)$$

Eqs. (1) and (2) yield reasonably accurate results under the following conditions [6]: • The diffracting aperture must be large compared with the wavelength λ; • The diffracting fields must not be observed too close to the aperture

2.1.1. DOE module description

Fig. 2 shows the diffractive optics module layout. The user can import the desired phase and intensity that needs to be simulated at the Input Plane using Upload Phase and Upload Intensity buttons. Other parameters such as Wavelength,Pixel size, Phase range, and Intensity range can be entered using the text boxes. The near and far field intensities can be viewed by clicking Fresnel at z and Compute Farfield buttons respectively. The user needs to specify the desired distance (z) in order to view near field intensity. The simulation results may be saved on to the disk using the save button, respectively.

2.2. GDSII conversion module

The next step after simulation is the fabrication of the physical DOE. Most lithography systems such as the Electron beam lithography (EBL) and Photo/UV lithography systems accept the DOE phase designs in only GDSII format. Often researchers have to rely on expensive software for this conversion step.

To address this important step in the DOE design cycle, we added the GDSII conversion module for the conversion of the DOE phase profile from standard image formats such as JPG and PNG to GDSII format.

Typical image to GDSII conversion processes involve creating a square pixel in the GDS file for each white or dark colored pixel in the image file. This process takes very long time and the output GDS file size is usually very large. In our approach, the desired phase image is first converted into a 2 dimensional array of gray values between 0 and 256. The algorithm then scans across the rows of the array and looks for any sequence of same-valued pixels in a row. If a sequence is found, the algorithm uses the first and last indices of the sequence to render it as a line segment in the output GDSI file. This line segment takes much less memory as it only represented

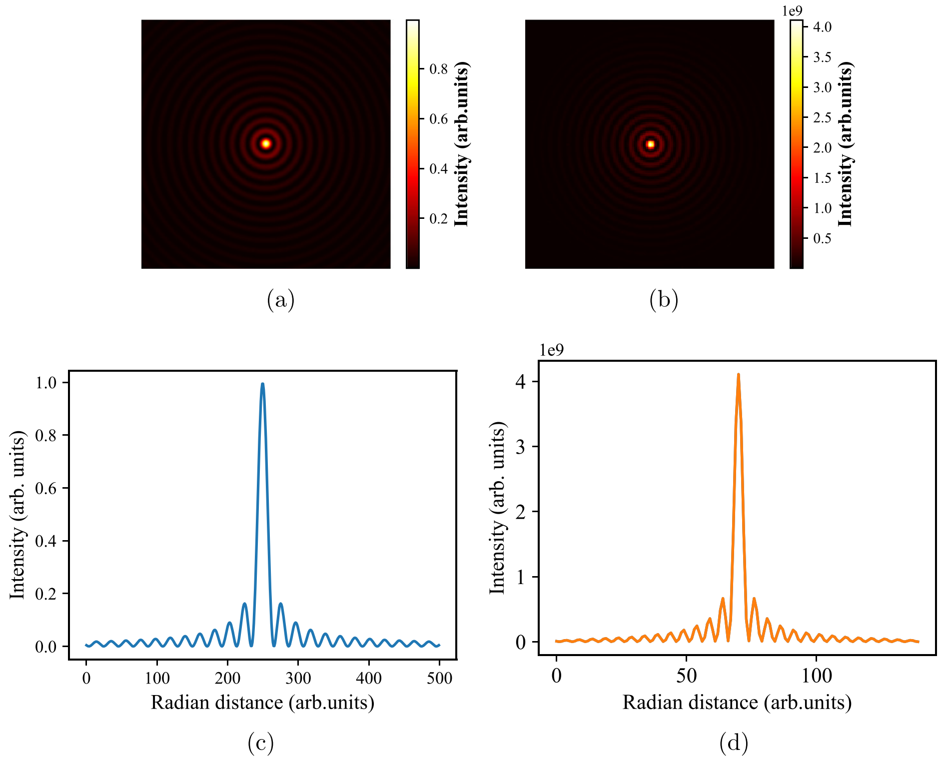

Fig. 8. Comparison between analytical and simulated Bessel beam (a) and (c) Transverse and line profile of analytical Bessel beam (b) and (d) Corresponding Transverse and line profile of *GDOESII* simulated Bessel beam.

by first and last pixels rather than all the pixels in the line segment. The grouping method used in our program is depicted in Fig. 3. The algorithm can also convert the image file into *n* layered GDSII files by quantizing the image to an array of *n* intensity levels. Presently the software supports conversion into 64 levels. However, the user is free to modify the source code to achieve as many levels as they wish. This is very useful for researchers working with 3D optical elements. As a world of caution, using too many levels can result in significant output file size and computational time. Fig. 4 shows the images converted using *GDoeSII* into 2, 4 and 8 levels respectively.

2.2.1. GDSII conversion module description

Fig. 5 shows the layout of GDSII conversion module. The pixel physical size needs to be entered in the text box. For grayscale images, the number of layers in the output GDSII file can be chosen from the dropdown menu. The software automatically quantizes the grayscale image into the desired number of levels before converting into the GDSII format.

Arrays of basic shapes such as circles, triangles and rectangles can be created using Periodic shapes (Fig. 6) menu. There are two models available. Mode 0 creates one unit cell and references it over an array of rows x columns, whereas Mode 1 creates an unit cell at each point in the array of rows x columns. Mode 0 generates very small file sizes compared to Mode 1.

The following parameters were measured to access the performance of the software. Fig. 7(a) shows the conversion times and output GDS file size for different sizes of the input image. Fig. 7(b) shows the conversion time and output GDS file size when a single image (2000 × 2000) was converted to multiple layered GDS files. However, these numbers can vary with the hardware capacity of the machine.

3. Illustrative examples

In this section we show two example cases. First we show the comparison between the analytical form of a Bessel beam and its simulated version. In the second example we show the comparison between simulated and experimentally generated Airy beam.

3.1. Example A: Bessel beam

Bessel beams [7,8] are so-called non-diffracting beams. Approximations to these beams can be experimentally generated using axicons. The analytical expression for a Bessel beam is given by,

$$E(r, \phi, z) = A \cdot \exp(ik_z z) J_0(k_r r), \quad (3)$$

where A is the amplitude, k_z and k_r are the longitudinal and transverse wavenumbers that satisfy the equation $k = \frac{2\pi}{\lambda} = \sqrt{k_z^2 + k_r^2}$ and λ is the wavelength. A Bessel beam can be simulated by computing the Fresnel integral of the phase profile of axicon with an incident Gaussian beam. Fig. 8(a) is the transverse intensity plotted using Eq. (3) and Fig. 8(b) is extracted from *GDOESII* simulation of the axicon and replotted to match the colormap of Fig. 8(a). Fig. 8(c) and (d) show the line plot along the center of (a) and (b) respectively. It can be seen that the simulation is agreeing very well with the analytical form of the Bessle beam.

3.2. Example B: Airy beam

In this section we show the simulation, fabrication and experimental results for the case of an Airy beam [9]. An Airy beam is a non-diffractive solution of the paraxial diffraction equation. The Airy beam can be generated using a cubic phase profile, which is shown in Fig. 9.

The phase profile shown in Fig. 9 is converted into the GDSII format and fabricated using an Electron beam lithography (Raith 150 TWO) system. These results are summarized in Fig. 10. Fig. 10(c) shows the experimentally generated Airy beam, which matches the simulated intensity profile shown in Fig. 9(b).

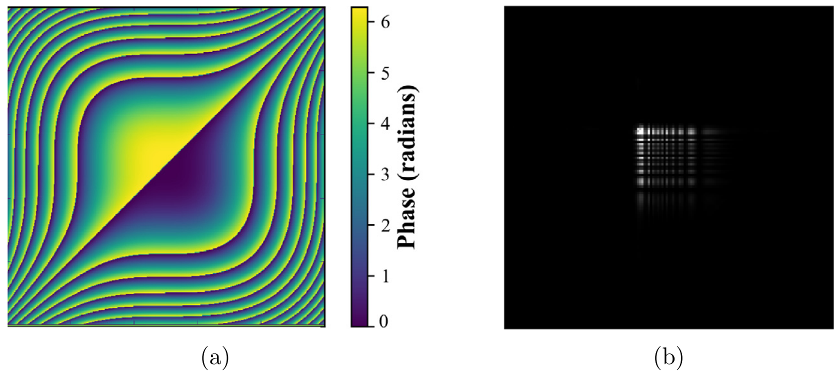

Fig. 9. (a) Cubic phase profile (b) Airy beam Intensity at $z = 10$ cm (Fresnel).

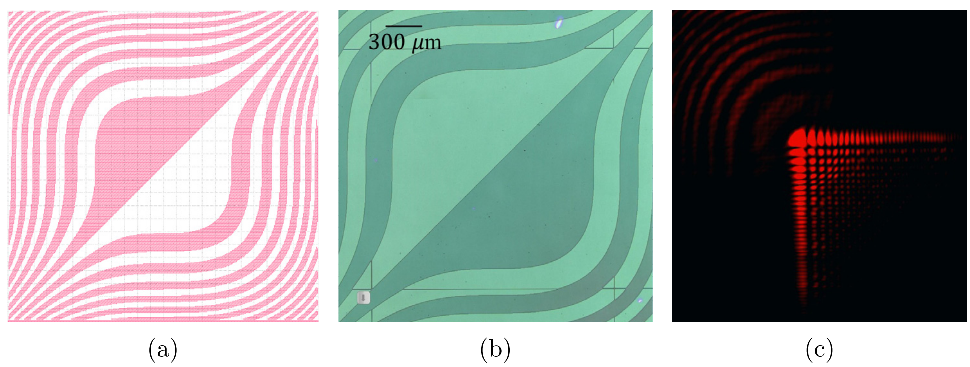

Fig. 10. (a) GDSII converted image (b) Confocal microscope image of the DOE (c) Experimental CCD image of the Airy beam.

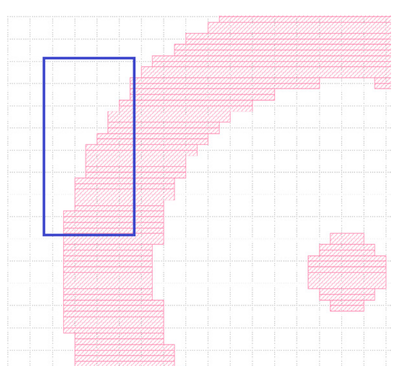

Fig. 11. Curved region in an example GDSII design.

4. Impact

Most often new researchers in this field rely on expensive software (E.g. VirtualLab Fusion (LightTrans Int) for their simulations. During the experimental part they again rely on commercial software such as LinkCAD to convert their phase designs from the image to the GDSII format, as most lithography tools do not provide the functionality of converting image files to GDSII format.

Apart from researchers working in Optics, the image to GDSII conversion module of *GDoeSII* will be very useful to researchers working in micro-nano lithography/fabrication.

5. Conclusions

We have introduced *GDoeSII*, a Python based software for Microsoft Windows platform which facilitates the computation of Intensity distributions produced by diffractive optical elements. This program also enables users to convert phase profiles from image formats such as JPG and PNG to GDSII (also multilayer) format in very less time, creating smaller file sizes. One problem with this conversion arises when there are curved features in the image file. Fig. 11 shows a curved segment of the GDSII file which clearly shows rough ridges. Future updates to the software will focus on improvements of the algorithm to accurately convert curved elements.

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