SAR – PHY – Optique – B: Fourier Optics and DOEs

Practical Class 3 – VirtualLab Fusion – Diffractive Optics

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1. Introduction

In this practical class we will use the same VirtualLab Fusion software that was used in practical class 1, but this time to design and simulate the operation of Diffractive Optical Elements (DOEs) as presented in the lectures.

To do this we will use the “Diffractive Optics Toolbox” of VirtualLab Fusion.
The design and simulation of a DOE in the software requires 3 distinct steps:

1. Definition of the optical setup and its parameters (light source, DOE size and resolution, diffraction regime, diffraction distance, simulated diffraction pattern size and resolution …)
2. Parametrisation and execution of the algorithm (IFTA) used to design the appropriate DOE (in fact one spatial period of the DOE’s transmittance)
3. Use of the created Light Path Diagram (LPD of the optical system as in practical class 1) containing the designed DOE to calculate the simulated output pattern for the system. Here a “real” size DOE made up numerous DOE periods is simulated.

Please note that if we are not careful about choices of the various system and algorithm parameters, the calculation load can become very high (for example a large component or output field sampled at high resolution) and the simulation times can become long and unusable. More details below.

As before, while progressing throughout the practical class, save representative output view results for inclusion in your practical class report file which will be used to evaluate and mark your work.

2. Diffractive Optics Toolbox basic operation

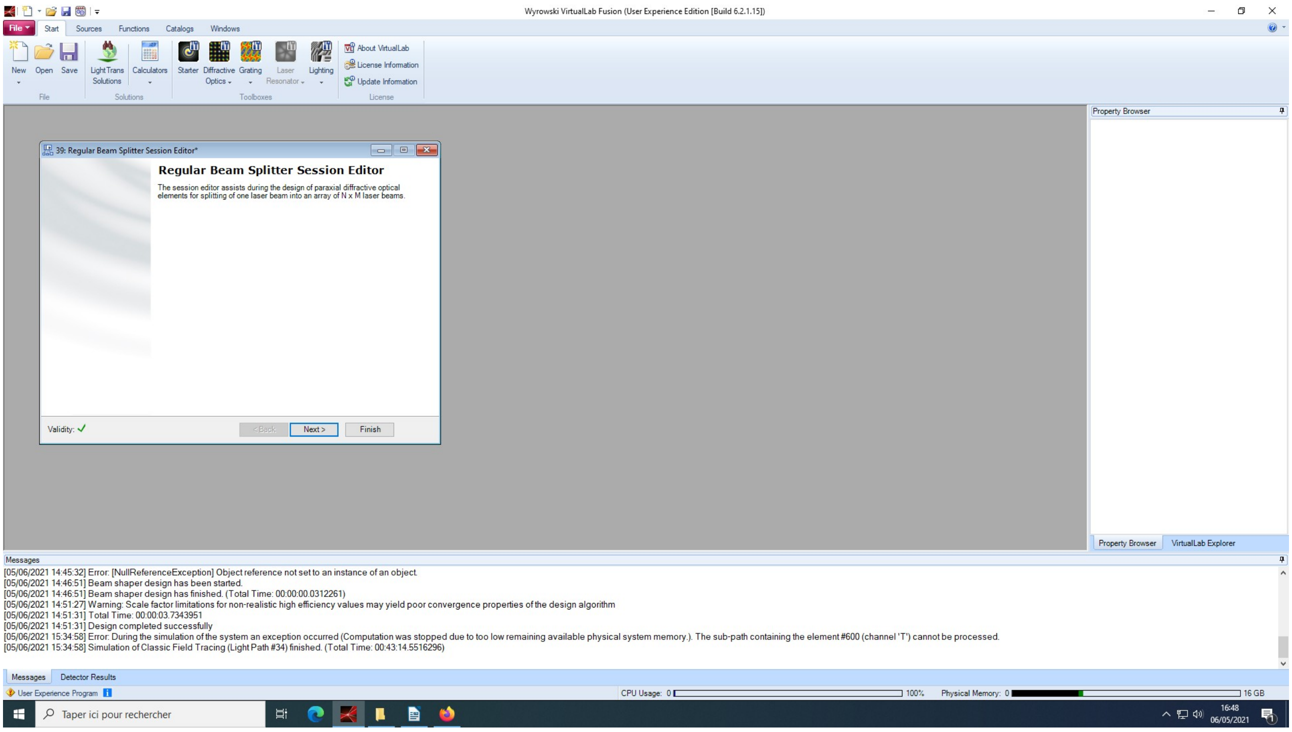
We will start by designing and simulating a typical simple DOE, a spot array generator, using default simulation parameters to gain familiarity with the software before moving on to designing and simulating DOEs with specific parameters for fabrication in the IMT Atlantique Optics Department fabrication facilities (cleanrooms). The Diffractive Optics Toolbox proposes several types of DOE (“Beam shaper”, “Diffuser”, “Beam Splitter” …), but in fact they are mostly just different presentations of the same basic DOE algorithm. Here we will only study and use the “Beam Splitter” type which can be used to calculate all the DOEs we require.

2.1 Regular Array Beam splitter DOE (Spot Array Generator)

In the first simulation we will design a Beam Splitter DOE or Spot Array Generator that splits an incoming laser beam into an array of separate light beams or spots. These are some of the most commonly used DOEs (see applications section of the lectures) because this optical function is difficult to perform using standard optical components.

The procedure to launch the software is the same as for Practical Class 1. If in a Linux PC room, log into the system then use the Remina software to distance connect to one of the Optics Department PCs (PC-OPT-994, PC-OPT-995, PC-OPT-998, PC-OPT-898). Once the Windows Desktop is open:

1. Launch **VirtualLab Fusion** (Desktop icon or Windows menu)
2. Click on the **“Diffractive Optics”** toolbox in the icon bar near the top of the VirtualLab window and select “Regular Array Beam Splitter”
3. This will open the Diffractive Optics “Wizard” which guides the user step by step through the parametrisation of the system and the DOE. Initially we will nearly always accept the proposed default parameters. Later, in the experimental section you will repeat the designs but with your own chosen parameters.



Below are indications of the main steps and the significance of the most important parameters in the Regular Array Beam Splitter Wizard.

<u>Input beam parameters (2 pages).</u>

First we choose how to parametrise the Gaussian profile laser beam illuminating the DOE. The default technique, which we will use, is to indicate the beam “waist” radius at $1/e^2$: the point at which the light amplitude has dropped to $1/e^2$ of the central peak value.

In the second window we choose the radius value and the laser wavelength. Accept default values

<u>Optical Setup (2 pages)</u>

The next step allows us to choose the optical setup, for example using lenses or long distance diffraction to perform a 2D Fourier Transform by diffraction.

Choose “Paraxial Far Field” and a diffraction distance of 1m

<u>Desired Output Field (2 pages)</u>

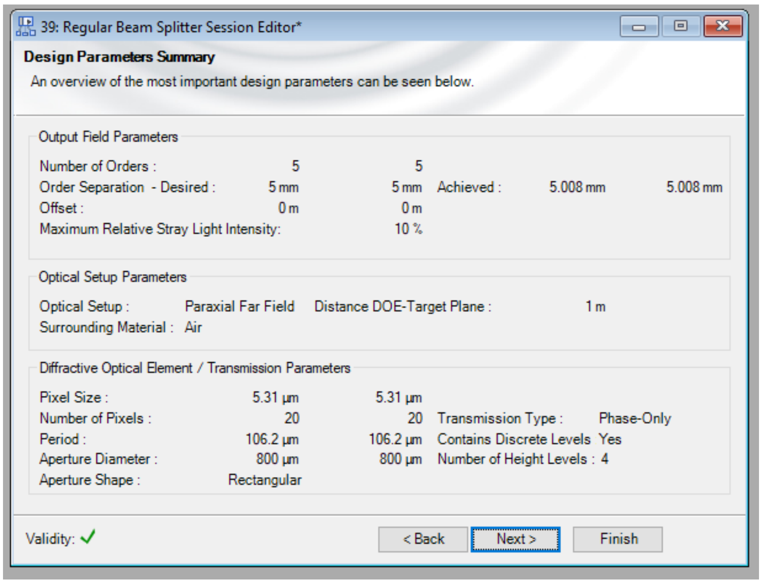
Here we can choose and parametrise the output diffraction pattern (“target” pattern) we would like the DOE to produce. In this case of a Regular Spot Array we can choose the number of spots in X and Y. Choose a 5x5 array of spots and a spot separation of 5mm in both directions. Leave the other parameters at their default settings.

The output field size that we simulate can be changed if required so that we can observe the noise field (stray light) around the simulated output pattern – here use the automatic setting.

<u>Merit Function</u>
This allows us to define which criteria we wish to optimise in the DOE design algorithms such as DOE diffraction efficiency or RMS (Root Mean Square) error or SNR (Signal to Noise Ratio) or a combination of several parameters. Use the default selection.

<u>DOE Parameters</u>
This allows us to define several DOE parameters, such as DOE physical size and DOE resolution (pixel size) generally determined by the capacity of the available DOE fabrication facilities.
Aperture size: use rectangular with automatic settings
DOE Transmittance – can be amplitude (B&W) or phase (etched glass) : choose phase.
Phase levels – use default (4 levels)
Pixel size – use default automatic setting

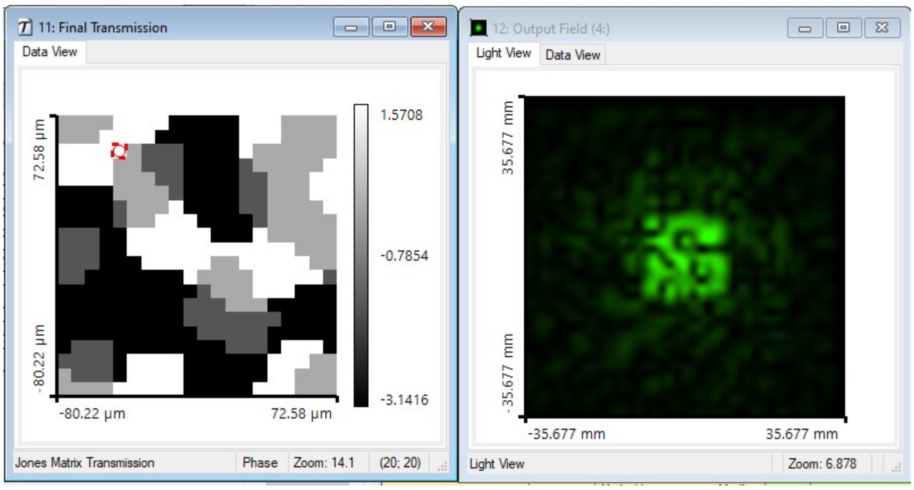
<u>Design Parameters Summary</u>
At this point the system and DOE specification is complete and the software shows a summary of the various parameters (it can be useful to save/note this information) and an indication (“Validity”) that the parameters are consistent and reasonable.



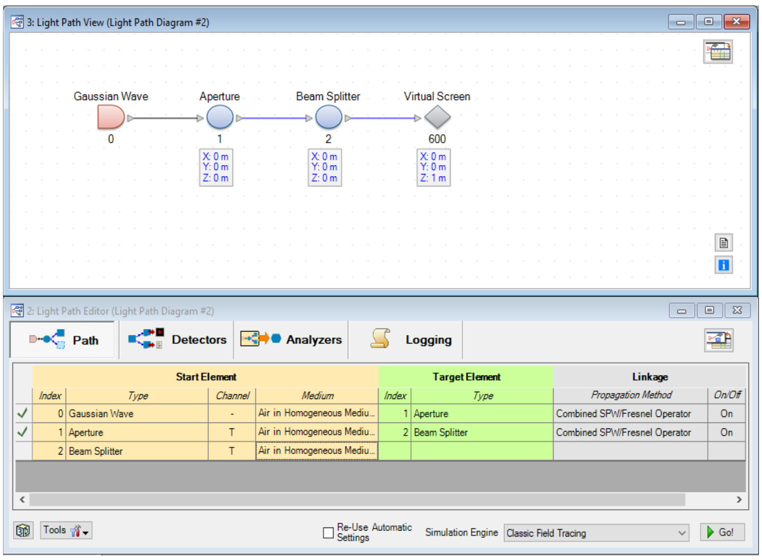
<u>Iterative Fourier Transform Algorithm Optimisation</u>
On clicking the “Finish” button after the Design Summary, the software creates the Light Path Diagram for the system in background windows and opens the DOE design algorithm (IFTA) dialogue box window. The IFTA algorithm is a multi-stage algorithm with specific numbers of iterations at each stage. The default values are reasonable apart from the final stage (“**SNR Optimisation**”) which uses a very large number of iterations, greatly extending execution times for little gain. Replace by **500 iterations**
Select also “Show Final Transmission and Output Field” so that we can visualise them.

Finally click “Start Design” to run the design algorithm.
After the calculation which can take several minutes for complex systems, the software should open two new windows:
- “Final Transmission” containing the calculated DOE transmission function
- “Output field” showing the simulated output pattern for **one** DOE period

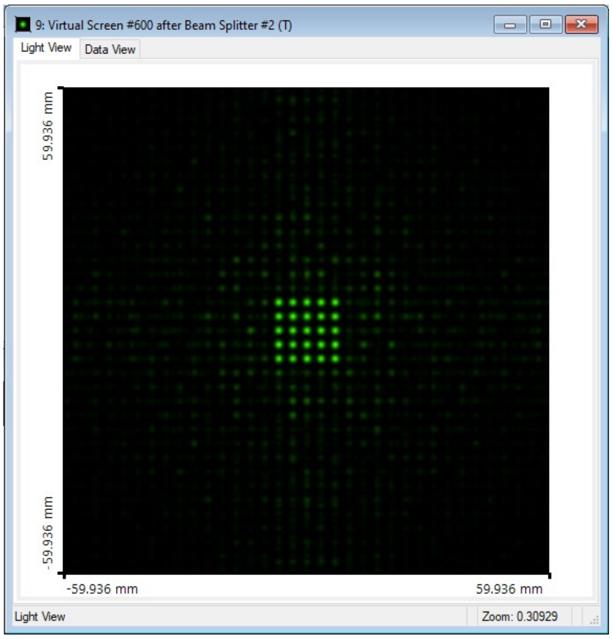
Note that by default the software shows the DOE amplitude and for a phase DOE the amplitude function is A=1 everywhere so the DOE transmission function image is white everywhere. To see the DOE phase function, click on the “Final Transmission” window and select the phase representation using the “f” icon in the top left.



At this stage the output pattern only corresponds to the result from a one DOE period so the simulated optical output pattern is strongly effected by noise (called speckle noise). By clicking on the “data view” tab you can see the sample points of the digital output field calculated and optimised by the IFTA algorithm. To simulate a more realistic “experimental” view of a physical DOE fabricated from several spatial repetitions of the basic DOE “unit cell” transmission and illuminated by a real Gaussian profile laser beam we must use the Light Path Diagrams. The corresponding Light Path Diagram windows for the system should have been automatically constructed and opened by the software (see below).



Click on the “Go” button to run the simulation of the realistic optical system – this can take some time as we are simulating the reconstruction of several (sometimes hundreds) DOE periods rather than just one. In this case the simulated output field should look something like the one shown below containing a regular array of 5x5 light spots.



As in practical class 1, you can use the software to measure various important parameters of the output light field such as:

- spot separation
- spot width
- diffraction efficiency (percentage of light in each spot or in all the spots ?)
- spot array uniformity (do all the spots have the same intensity ?)
- …

2.2 Irregular Beam splitter investigations

Based on this initial design we now study how the various system and DOE parameters effect the output pattern obtained.

<u>Optical System modifications (same DOE)</u>
Using the DOE calculated above, change the following parameters in the Light Path Diagram (LPD) to see how the DOE behaves in different optical systems:

1. Change the diffraction distance – how does this effect the output pattern shape/size ? Explain the changes observed – quantitatively if possible.

2. Change the input beam size – how does this effect the output pattern shape/size ? Explain the changes observed.

<u>DOE modifications</u>
Close all the VirtualLab windows and recalculate (same procedure as above) a new DOE with different parameters.

1. Different numbers of spots and different separations. The array doesn't need to have the same numbers of spots, nor separations in X an Y. Do not use too many spots (< 25x25) to avoid long calculation times.

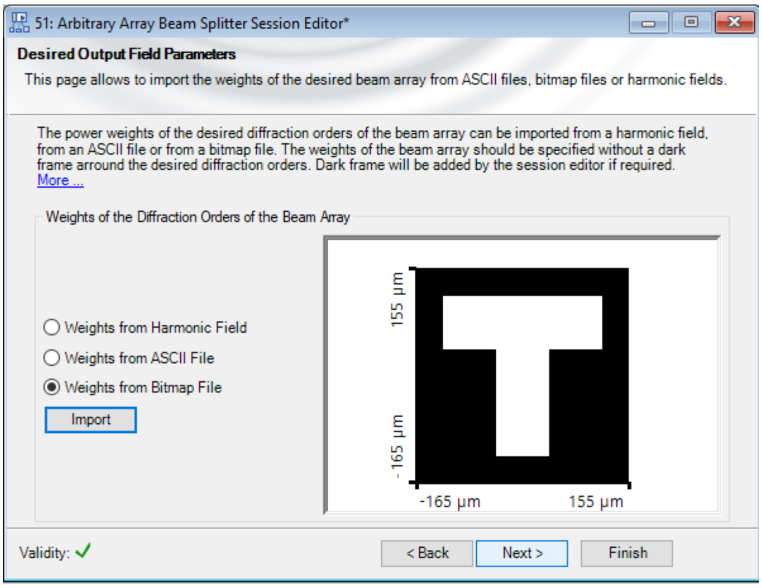
2. Calculate a DOE for a different wavelength – for example 632.8nm used in the optical lab experiments.

3. If time permits, experiment with the other possibilities offered by the software in the calculation of Regular Beam Array DOEs...

2.3 Arbitrary Array Beam splitter

So far we have only calculated DOEs generating arrays of spots where all the spots have the same intensity. We will now learn how to calculate DOEs generating spot arrays where the intensity of each spot can be different. In this way we can design DOEs generating output "images" rather than regular "blocks". Producing truly continuous images is difficult with DOEs because of "speckle" effects but by placing spots close together (but avoiding overlap) when the image is observed from a suitable distance the observer doesn't see the individual spots and the image appears continuous.

Close all the VirtualLab windows and select the "Arbitrary Array Beam Splitter" in the "Diffractive Optics Toolbox". The Wizard interface is very similar to that presented above (follow the same steps) **except** for the "Desired Output Field" pages where we have some additional options:



Select the "Weights from a Bitmap File" option and click on "import" which will allow you to import weights to assign to the different array spots using the pixels of a grey-level bitmap image. You can prepare an image to upload using "paint" or "Gimp" for example – to avoid long DOE calculation times choose simple images with fewer than 50x50 pixels for example. Several image file formats are accepted – *.png is recommended.

Once the image is uploaded, continue the Wizard parametrisation procedure as before – you may have to adjust the output spot separation to reasonable values. (For a 50x50 pixel image at a diffraction distance of 1m and a 1mm diameter illuminating laser beam, an output image of 15cm is reasonable so a roughly 3mm spot separation should be OK).

Complete the rest of the DOE and system parametrisation procedure and the design of the DOE as before and then study the DOE phase pattern and the diffracted output pattern shape, size, noise distribution and estimate the diffraction efficiency of the DOE.

As above, study and **explain** the effects of modifications in the optical system design and in the parameters of the DOE. In particular investigate:

1. The effect on the output pattern and the diffraction efficiency of using an **amplitude DOE** (change the selection in the “DOE Transmission Parameters” window of the Wizard design procedure).

2. The effect on the DOE, the output pattern and the diffraction efficiency of using phase DOE with **different numbers of phase levels** – for example, 2, 4 and 16 levels. (Change the selection in the “DOE Transmission Parameters” window of the Wizard design procedure).

3. The effect of **offsetting** the target pattern’s position in the output plane: moving it away from the optical axis. (Change the selection in the “Desired Output Field Parameters” window of the Wizard design procedure). How does this affect the DOE phase pattern ?

4. Experiment with other DOE modifications as time allows.

3. Design your own DOE for fabrication

To finish the practical class, and to apply all you have learnt in a practical case, each **group** should calculate and save their own DOE which we will try to fabricate in the Optics Department cleanrooms in time for you to measure and analyse experimentally in the final laboratory practical class.

<u>DOE characteristics</u>

When calculating your DOE with the software, please use the following parameters:

Wavelength : 632.8nm = the wavelength of the lasers used in the laboratory practical classes

DOE transmittance : binary phase (2 level pure phase) = the easiest to fabricate reliably

DOE pixel size : 750nm. (Force this using the “Manual selection” option in the DOE parameters page of the wizard. This is the plot grid of the cleanroom photoplotter but individual DOE pixels of this size will not necessarily be resolved so check that your DOE transmittance profiles do not contain too many isolated pixels

The other parameters can be chosen more freely – but are also mutually dependent. Below are some guidelines to reasonable values which give good results.

Diffraction distance : 1 to 2 meters in the “1F lens” diffraction configuration is a good compromise and close to the configuration of the optical benches in the laboratory

Output image: for good results use relatively simple output images (<150x150 pixels) and diffraction angles of about 5° maximum. For example for a 100x100 pixel image at 1m, this gives an image size of roughly 10cm so a spot separation of the order of 1mm

DOE period: DOE periods of roughly 1000pixels are a reasonable compromise in terms of calculation time, image complexity and spot size.

Input beam size : 1mm radius (2mm diameter) is a reasonable maximal value

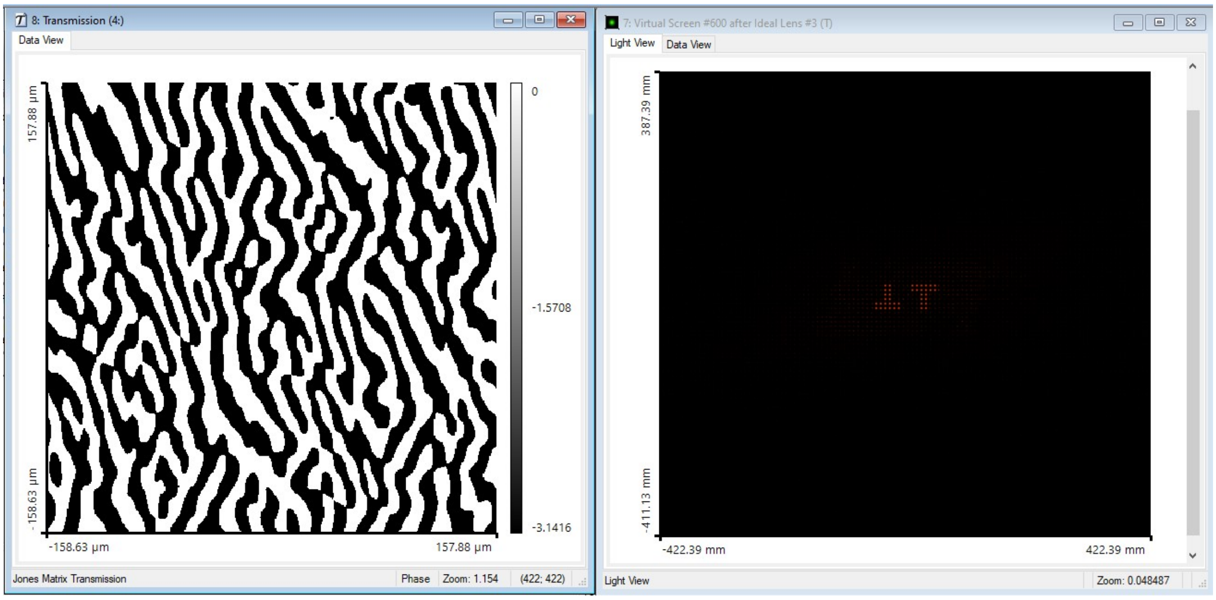
DOE aperture size : 4mm square is a maximum value to avoid long simulation times.

Off-axis : Since the DOE is binary phase, the output field will contain a conjugate image. If the image is symmetric an on-axis image is possible. Otherwise the target image must be placed off-axis to avoid overlap with the conjugate image. Use just enough off-axis translation to separate the images but avoid large diffraction angles and many isolated DOE pixels (difficult to fabricate).

Below is an example of an output field view for a reasonable DOE and a view of the corresponding DOE binary phase transmittance.

The final DOE transmittance file should be exported in *.png format by selecting the appropriate window and then choosing “Export” → “Export as image” in the “File” menu. You must select the “Phase” to be exported in the “Field Quantity” selection of the “export” dialogue box – check the image data that will be exported by using the “preview” facility. The image you see should be the phase of the DOE you have calculated. Ask the Practical Class supervisor if you are uncertain.

Email the exported file to kevin.heggarty@imt-atlantique.fr



Supplementary exercises

If time permits and you are motivated you may continue to investigate the possibilities of the VirtualLab Diffractive Optics toolbox. Possible examples:

1. Investigate the use of the "Regular diffuser" and "Arbitrary diffuser" toolbox options. These attempt to calculate DOEs which produce continuous output patterns (rather than output "spots"). With highly coherent laser sources the output will generally contain strong speckle but with reduced coherence sources, speckle is reduced.

2. Illumination of DOEs with reduced coherence illumination sources. In the LPD modify the light source by increasing the spectral width or the number of modes

3. DOE fabrication error and tolerances. In practice it is difficult to fabricate perfect DOEs. Fabrication technology has limited resolution for example so pixels become rounded and etch depth is rarely controlled sufficiently to give exactly a Π phase change. This can be simulated by opening the calculated DOE (double click on "Beam Splitter" in the Light Path Diagram), checking the box "Impose Linear Error by Scale Factor" and then using, for example, a factor 1.05 to simulate an etch depth that is 5% more than required.. This should produce a stronger "zeroth order" undiffracted light spot in the output pattern.