Design of Binary Phase Plates using LabView

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Introduction

For many years the Vulcan laser has successfully pursued plasma physics experiments using "in-house" designed and manufactured binary phase plates to generate large focal spots (typically 10 - 100 times diffraction limit). Predominately, these spots have been of sinc^2 or pseudo top-hat intensity profiles, produced by Random Phase Plate (RPP)[1] or Phased Zone Plate (PZP)[2] designs respectively.

However, both the RPP and PZP focal spots have limitations in their use in that although the PZP can be used where a sinc^2 profile is not ideal, the top-hat profile itself is not completely uniform. Also, as experiments have become more demanding in terms of the physics being researched, so have the demands for focal spot manipulation. Traditionally the RPP and PZP designs have been based on very simple scaling parameters, this paper describes a more rigorous computational approach to phase plate design using LabView[3] which is able to generate not only much more homogeneous top-hat intensity profiles, but more arbitrary focal spots such as an array of stripes.

Computation

Phase plates are generally used to alter the far-field focal spot distribution in conjunction with a principal focusing optic. Since a lens is a "Fourier Transform device" this means that a Fast Fourier Transform (FFT) is useful in computing new phase plate designs. As applying a FFT to a particular input beam intensity and phase profile leads to an indication of the focal spot distribution; it is reasonable to apply the process in reverse and define a desired focal spot intensity and phase profile and then calculate, via an inverse FFT, the input beam required to achieve this. Of course there is then a problem in that it would be extremely difficult in practice to produce the prescribed arbitrary phase and intensity profiles.

To overcome this issue, constraints on the far-field phase profile are lifted and an iterative process applied as shown in Figure 1. The input beam, with the known intensity and a "best-guess" phase profile, is initially transformed to the far-field where the *calculated* intensity profile is discarded, being replaced by I_D, the *desired* focal spot intensity distribution (leaving the phase profile θ_F untouched). This new combination is then inverse transformed back to the input plane where the newly calculated intensity profile is discarded being replaced by the known input intensity profile. The calculated phase distribution (which has a range of $\pm\,\pi$) is again left untouched as this provides the next "best-guess" input for the following iteration.

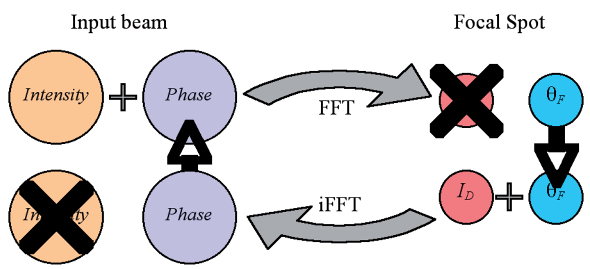

Figure 1. Gershberg-Saxton algorithm applied to the phase plate design.

This is the essence of the Gershberg-Saxton algorithm[4] which generally and readily converges to a stable solution for the input phase profile where the calculated and desired focal spot intensity profiles are well matched.

Once the continuous-phase solution calculated by the inverse FFT has become reasonably stable, (typically requiring no more than 25 iterations), the profile is "binarised" to produce the final phase plate design.

The initial binarisation method that was applied to the $\pm\,\pi$ continuous phase profile was to take the absolute value of the phase and then use a threshold of $\pi / 2$ to force the 0 to π binary phase step. This gave a reasonable binary phase plate design but the FFT intensity plots often indicated a significant residual zeroth order intensity. Manufacturing tolerances in producing the phase plate from any design tend to produce an unwanted contribution into the zeroth order in any case so starting from a design that already has a central spike is not ideal.

To eliminate the zeroth order it is necessary in practice to have perfect balance between the zero phase and π phased areas. To produce a design more closely balanced the binarisation method was changed to simply order the continuous phase data, calculate the median value and then use that as the threshold level instead. This method still gave a good intensity distribution and always calculated minimal zero order contribution.

LabView Program

A screenshot of the LabView program in action is shown in Figure 2. The main features of the front panel are (Fig 2a) the input parameter area where the initial input beam intensity and phase distribution, the working wavelength, beam size, focal length and the desired focal spot distribution and profiles can be defined. Fig 2b, the set of graphs indicating (left) the initial phase distribution of the input beam, (centre) the FFT intensity, and (right) a plot of radial profiles taken from the FFT data. Fig 2c, a row of a similar set of graphs showing the calculated continuous phase distribution required, the FFT intensity and the radial profiles for each iteration. Fig 2d, a further set of graphs, generated after the initial binarisation process, showing the input phase and far-field intensity distributions and the radial profiles.

(a)

(b)

(c)

(d)

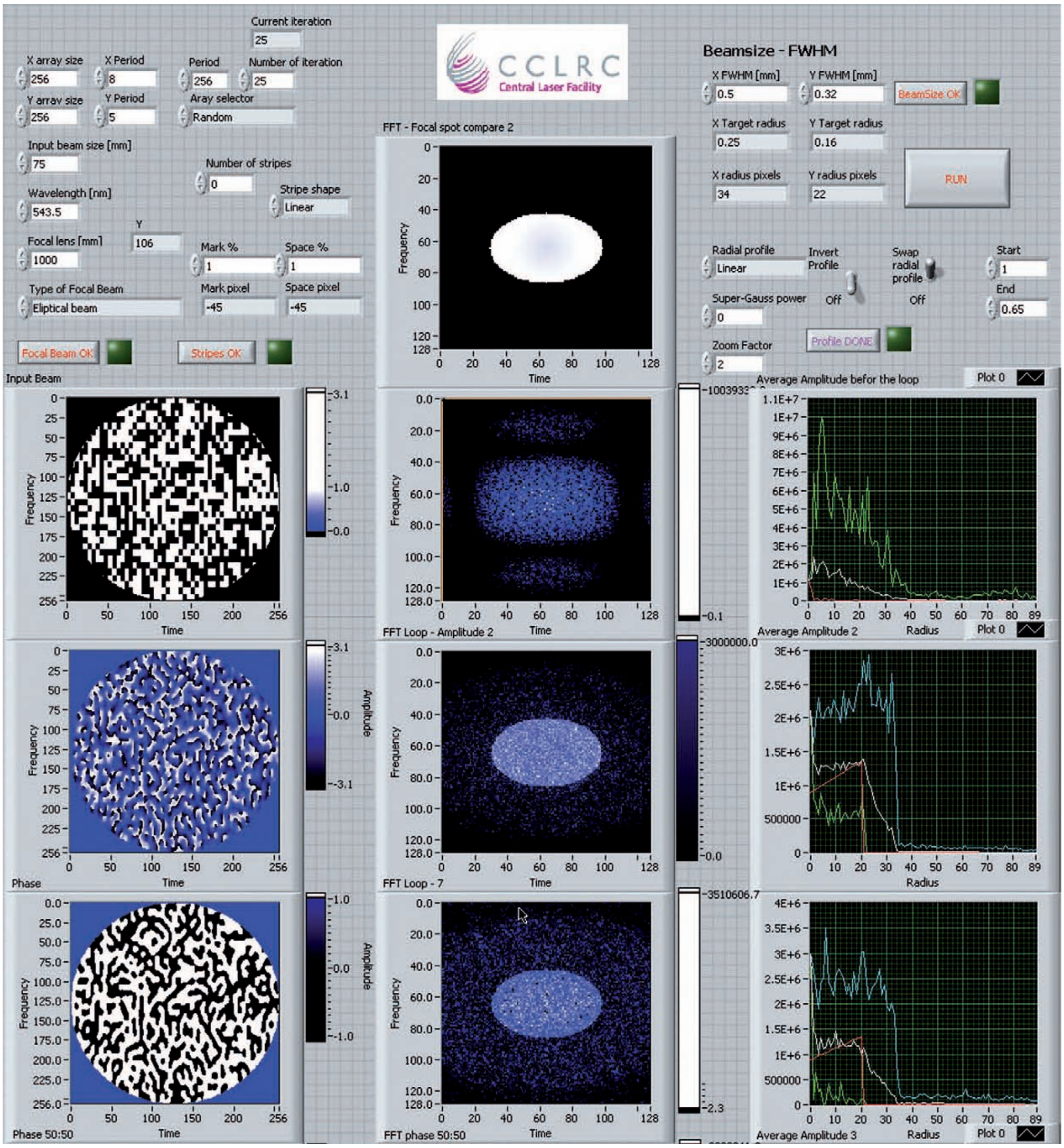

Figure 2. Screen shot of the LabView design program showing a) the numerous input parameter controls and b), c) and d) the 3 main output rows each of which are displaying graphs of the near-field phase distribution (left), the far-field intensity distribution (middle) and the radially averaged intensity line-outs (right).

As can be seen by comparing the FFT images, the intensity distribution generated by the standard RPP design (Fig 2b) is significantly improved upon by the continuous phase design (Fig 2c) being far more defined and uniform. This is not unexpected but the worth of the design process is seen in the further comparison to the binary-phased version (Fig 2d). Although (compared to Fig 2c) there is an decrease in overall uniformity and an increase in the intensity of the surrounding area, it is readily apparent that compared to the sinc^2 profile of the original RPP design, there is still expected to be a very significant improvement in focal spot definition and uniformity with the new binary version.

Manufacture

Having achieved a design through the LabView program the binary pattern is saved to a file and printed on an acetate film in a high-resolution imagesetter. The acetate film is then used in a photo-lithographic process to manufacture the final binary-phase optic which is a layer of photo-resist spin-coated onto a glass substrate.

Results

The manufacturing process has a number of stages where errors can arise (such as with the accuracy of the phase step) that lead to a small amount of undiffracted light contributing to a zero-order central spike in the principal

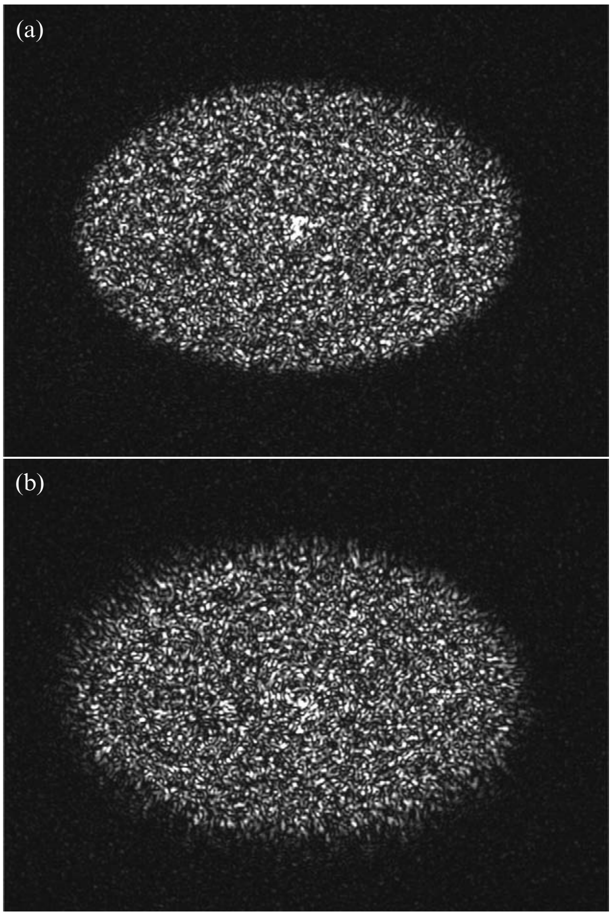

Figure 3. Images of the focal spot distributions produced from the optical phase plates designed using the LabView program; a) at the principal focal plane and b) defocused by 3 mm.

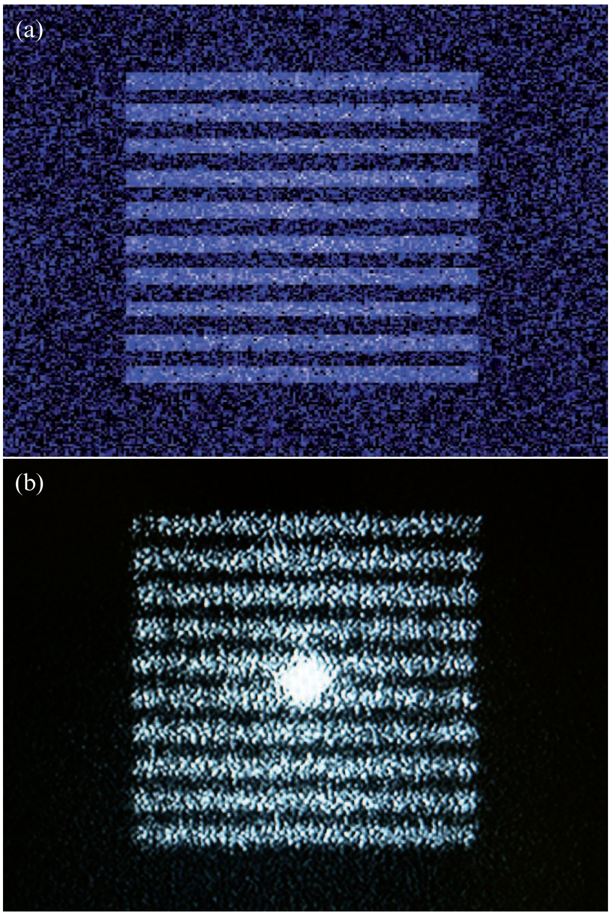

Figure 4 Generation of a striped focal spot; a) The final FFT output from the LabView design and b) the optical focal spot obtained from the acetate mask.

focal plane of the main focusing optic. Figure 3a shows the optical image obtained from the physical phase plate and clearly shows the good edge definition and overall uniformity of the focal spot and the central spike due to the residual zero-order. Despite the presence of the spike this is an excellent result and proves the LabView program design process is working well.

As with existing RPP and PZP phase plates the effect of the residual zero-order can be minimized by a slight de-focus. As the zero-order is simply part of the geometric focus, it will expand rapidly whereas the much larger diffracted focal spot expands more slowly. A typical defocus distance is that which produces a geometric focal spot size ~10% of the diffracted spot size. With the optical setup used for this experiment the defocus distance is 3 mm and Figure 3b shows the effect of this de-focusing. The result is that the edge is somewhat blurred but the central spike is essentially eliminated and the focal spot still retains good overall uniformity. Measurements have also shown that, taking into account Fresnel losses, the diffraction efficiency of this plate is around 70%.

These are extremely encouraging results which demonstrate that the program is easily and quickly able to deliver designs for good quality focal spot distribution and intensity profiles.

As an example of the flexibility of the program a phase plate was designed to produce a square focal spot with 10 evenly spaced and linear stripes across it, each with a uniform intensity. Figure 4a shows the expected far-field intensity distribution as generated by the final iteration of the FFT in the LabView program. Unfortunately, due to manufacturing problems at the time of this report is was not possible to produce a phase plate of this design with the correct phase step. It should be noted therefore that the optical focal spot shown in Figure 4b was generated from the amplitude mask printed on the acetate film. Because there is then no compensating phase step the central spike is particularly intense. Nonetheless the pattern of stripes is clearly seen and gives further indication of the benefits that the program will bring to the field of focal spot manipulation.

Conclusion

It has been demonstrated that the phase plate design program implemented in LabView produces viable binary phase plate designs with improved beam uniformity over previous RPP and PZP designs.

The results seen so far have been quite exciting and have given a high level of confidence that complex focal spot distributions and intensity profiles are easily within reach.

It is further expected that this new design method will have a significant impact on the experimental plasma physics programme not only within the CLF but for other high power laser systems around the world.

References

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