Modeling and Testing Array Generation Techniques for Grid Image Refractometry on OMEGA EP

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Abstract

Grid imaging refractometry (GIR) is a method of measuring the density profile of a plasma region that is too large to be effectively measured using interferometry. A grid of beamlets generated by a laser is sent through the plasma and refracted. The refracted grid is imaged and the deflection of each grid point is measured to back calculate the plasma's density profile. GIR will be implemented onto the fourth-harmonic probe beam on the OMEGA EP laser. A GIR system was designed and built to test the effectiveness of array generation using a physical grid or a three beam interferometer. A three beam interferometer was built and produced a hexagonal pattern that could be used as a grid. Use of a three-beam interferometer allows arrays to be generated with substantially higher frequencies without facing detrimental diffraction effects.

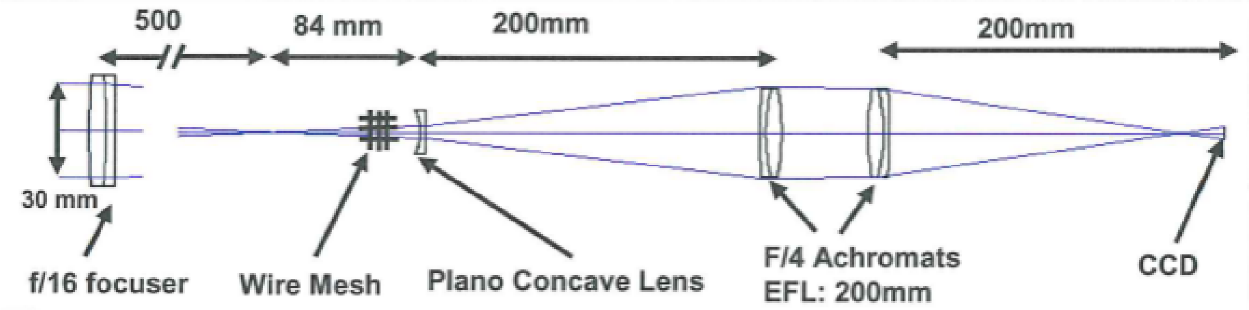

Figure 1: Model of the GIR setup. The plano-concave lens is used to represent the plasma

1. Introduction

In laser fusion, a plasma is produced when a laser is focused onto a target. The plasma is a hot, ionized gas that expands back towards the laser. The density of this plasma can be measured because the refractive properties of plasma at different densities are well known. Interferometry has been used to measure the density of the resultant plasma, but works only with smaller plasma volumes. Grid imaging refractometry (GIR)[1] is better suited for measuring larger plasmas, and will be implemented on the fourth-harmonic probe beam on the OMEGA EP laser at the Laboratory for Laser Energetics.

The basic setup of GIR is outlined in figure 1. This approach splits a collimated beam by sending it through a grid placed in front of a plasma. Each beamlet refracts differently with the varying refractive index of the plasma, which depends on plasma density. A collimating optic images the whole grid along different planes within the plasma. The deflection angle of each grid point is then calculated by subtracting the x,y coordinates of each corresponding grid point in different images. This process was automated using Matlab.

2. Optical Setup

A small scale GIR system was built to model the design for the OMEGA EP laser. The GIR system was built in stages to make modifying or testing a different stage easier. The system starts from a 30 mm collimated laser source to match the GIR design for OMEGA EP, and is put through an array generation assembly to create a grid of beamlets. The new grid is sent through a refractive target (the plano-concave lens in Figure 1) to simulate the plasma and finally through an imaging relay (the two f/4 achromats in Figure 1) to a CCD, where the image is saved and processed.

The setup tested two different methods of array generation, and gathered distorted images from different refractive targets. Instead of installing the GIR system in a real fusion system, the GIR system built used simulated plasma to make modifying the system faster, and limit the use of materials destroyed or consumed during the experiment[2].

2.1. Up-collimation and Refocusing

The system built for testing uses a laser produced at a 1.5 mm diameter. To match the fourth harmonic system, the beam was up-collimated to a 3.0 mm diameter. The input laser produces a beam with a Gaussian intensity profile. To eliminate the Gaussian intensity profile, a very fast aspheric lens is used to overfill the collimating lens. An achromatic lens is used as the collimating lens to help eliminate spherical aberration. The design was proposed and modeled in OSLO, and showed negligible amounts of aberration and intensity variation in the beam.

2.2. Imaging

The GIR system built uses two f/4 achromatic lenses to focus the refracted grid image onto a CCD. One lens samples the plasma region and the other lens focuses it onto the CCD. The focusing lens must be stationary at one focal length from the CCD, to prevent change in magnification while allowing the sampling lens to move. The sampling lens gathers grid images at its focal point. The lens can be moved to capture images at different distances along the imaging axis. The function of grid distortion relative to displacement along the imaging axis is needed to calculate the ray refraction.

A more advanced imaging system has been designed for implementation into the fourth harmonic probe. This system uses a semi-reflective beam splitter at an angle with a 100 m focal length mirror. Each time the beam is reflected between the beam splitter and mirror, it is shifted farther off axis, and the image of the plasma is moved farther along the optical axis. The system uses the first three beams that exit the system and images them onto a single CCD camera. This system allows for images at multiple planes to be captured simultaneously without the need for holography.

2.3. Array generation

The array is generated at some point before the f/16 lens in Figure 1 focuses the beam to the target region. It is necessary to focus the beam down from the original size of 30 mm in diameter so it has enough energy to overcome plasma self-emission. The final grid image sampled is about 5 mm in diameter, the size of the plasma to be diagnosed. The beam is not initially started with a high enough power density to overcome plasma self-emission, because if it did, the beam would damage any optic it passed through. The beam sizes were chosen to effectively match the GIR plan for the fourth-harmonic probe beam.

2.3.1. Wire mesh

In the GIR system being implemented on OMEGA EP, the array is generated by placing a wire mesh along the beam path close to the sample region, held in place by a Ten-Inch Manipulator. The wire mesh will be destroyed on each shot, either by the plasma or by the probe beam.

Diffraction from a physical grid limits the imaging distance from the object plane. The diffraction effect is known as the Talbot effect. The Talbot effect occurs when light from evenly spaced sources diffracts and interferes. The Talbot effect causes the light to reform an array at regular intervals along the optical axis. The interval between successive reformations is called the Talbot length. At the half Talbot length, the image is reformed but phase shifted by the period. At the quarter Talbot length, the image is reformed but with double frequency. Figure 2 shows the Talbot carpet, an example of the interference effect across a plane. In this figure light is passed through the evenly spaced slits seen at 0 Talbot length. As the light propagates to the right, it diffracts and interferes. There is only a small range in the Talbot carpet where there is enough contrast, such that the interference peaks are less than 50% of the grid point's intensity peak, to be able to use a program to distinguish grid points that can be correlated with the original grid image.

The Talbot effect was studied by taking images across the Talbot length. The images (shown in relation to distance in Figure 2) determined the length of the usable region for imaging, based on contrast of the grid. The Talbot length was calculated with the formula:

$$L = \frac{2a^2}{\lambda} \tag{1}$$

where L is the Talbot length, a is the grating period of the mesh, and λ is the wavelength. For our setup, $a = 91\ \mu\text{m}$, $\lambda = 543$ nm, so $L = 30.5$ mm. This Talbot length was convenient since, because in the optical setup used (Figure 1), we had around 40 mm of movement space before the grid image became two small for grid points to be distinguished.

Images were gathered by moving the imaging lens 1 mm away from the refractive medium from

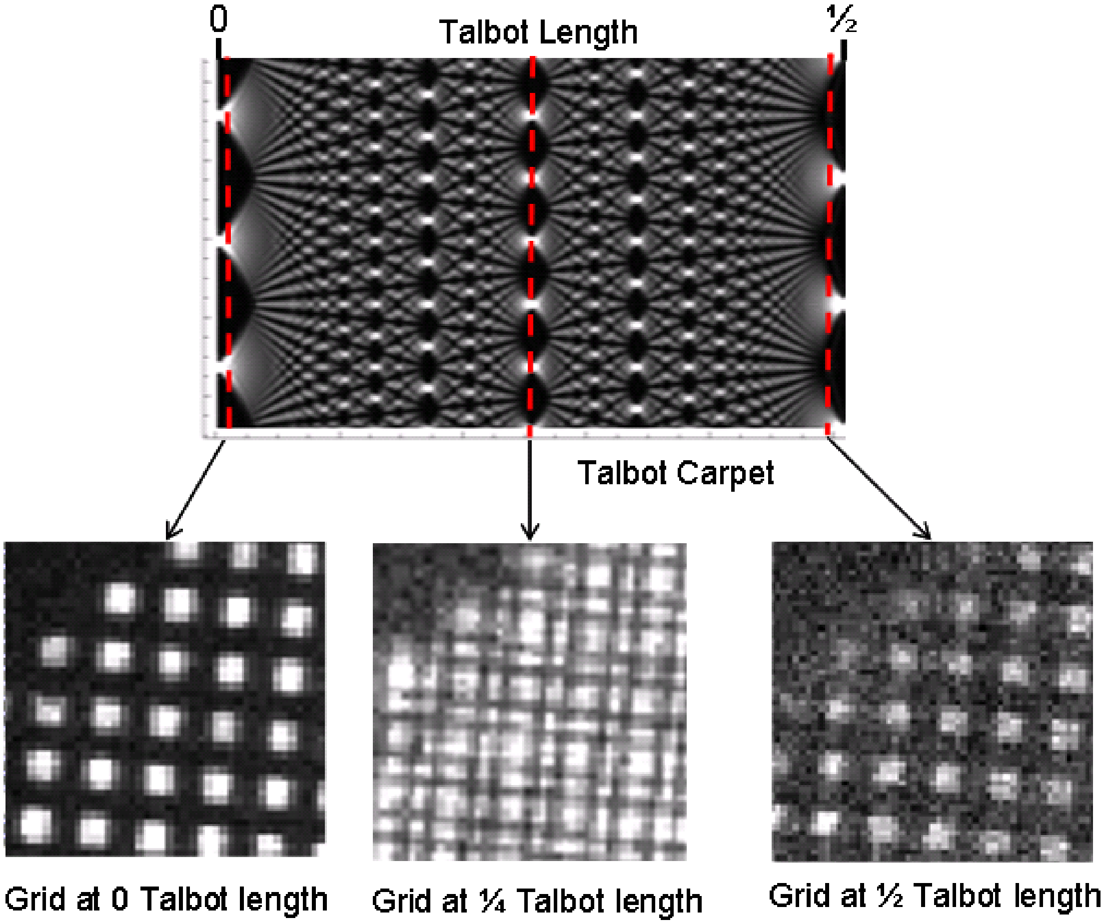

Figure 2: Talbot Carpet and three grid images, representative of their marked 1D section on the Talbot Carpet. The Talbot Carpet is an example of the Talbot effect, where light from evenly spaced sources diffracts and interferes. The images at the 0 Talbot length and the 1/2 Talbot length are usable, as determined by taking a lineout of intensity across grid points and showing interference peaks were less than 50% of a grid point's peak. These two images have grid points that can be correlated, while the 1/4 Talbot length image has no discernable grid points to correlate. This is due to the double frequency effect seen in the Talbot carpet at the 1/4 Talbot length.

its initial distance of 200 mm, the lens' focal length, until the grid points seemed distorted. The light intensity was averaged over three grid points for each grid image (Figure 2). An unusable grid image was determined to be where the modulation depth was less than 50% of the grid point's peak intensity. The range where usable images were produced was determined to be approximately 5% of the calculated Talbot length. At the quarter Talbot length, the double frequency image was not usable.

From Eq. (1), the Talbot length increases quadratically as the mesh period is increased.

2.3.2. Three beam interferometer

A second method of array generation was explored in response to the limitations of the physical grid.[3] An array was generated by interfering three beams together (Figure 3). Figure 3 (a) shows how the beams are interfered. MATLAB was used to simulate this interference based on the real part of the electric field equation. The intensity is found by summing each beam's electric field and multiplying the sum by its complex conjugate.

The azimuthal (ϕ) and zenith (θ) angles of the incident beams were then manipulated to show that the hexagonal grid generated by three beam interference could be controlled. Figure 3 demonstrates how the grid orientation and frequency change by θ and ϕ. In Figure 3 (b), the beams are interfered at $\theta = \pi/24$ and $\phi = 2\pi/3$. In image (c), one of the three beams' azimuthal angle, ϕ, was moved by $\pi/6$ distorting the grid. A frequency change is shown in Figure 3 (d), where θ was changed to $\pi/6$.

A three beam interferometer was built in the lab (Figure 3 (e)). A single beam was split into three using two-beam splitters, and the three three beams were recombined using two more beam splitters. To combine two beams, one is reflected and the other is propagated through. The azimuthal and the zenith angles of two beams can be changed by rotating a beam splitter using a gimbal mount. The three beam interferometer allows for a large range of azimuthal and zenith angles, giving complete freedom in the array frequency. The interferometer was tested to produce arrays with periods as small as 20 μm. Test images taken of the three beam interferometer's array showed high contrast up to 90% (Figure 4).

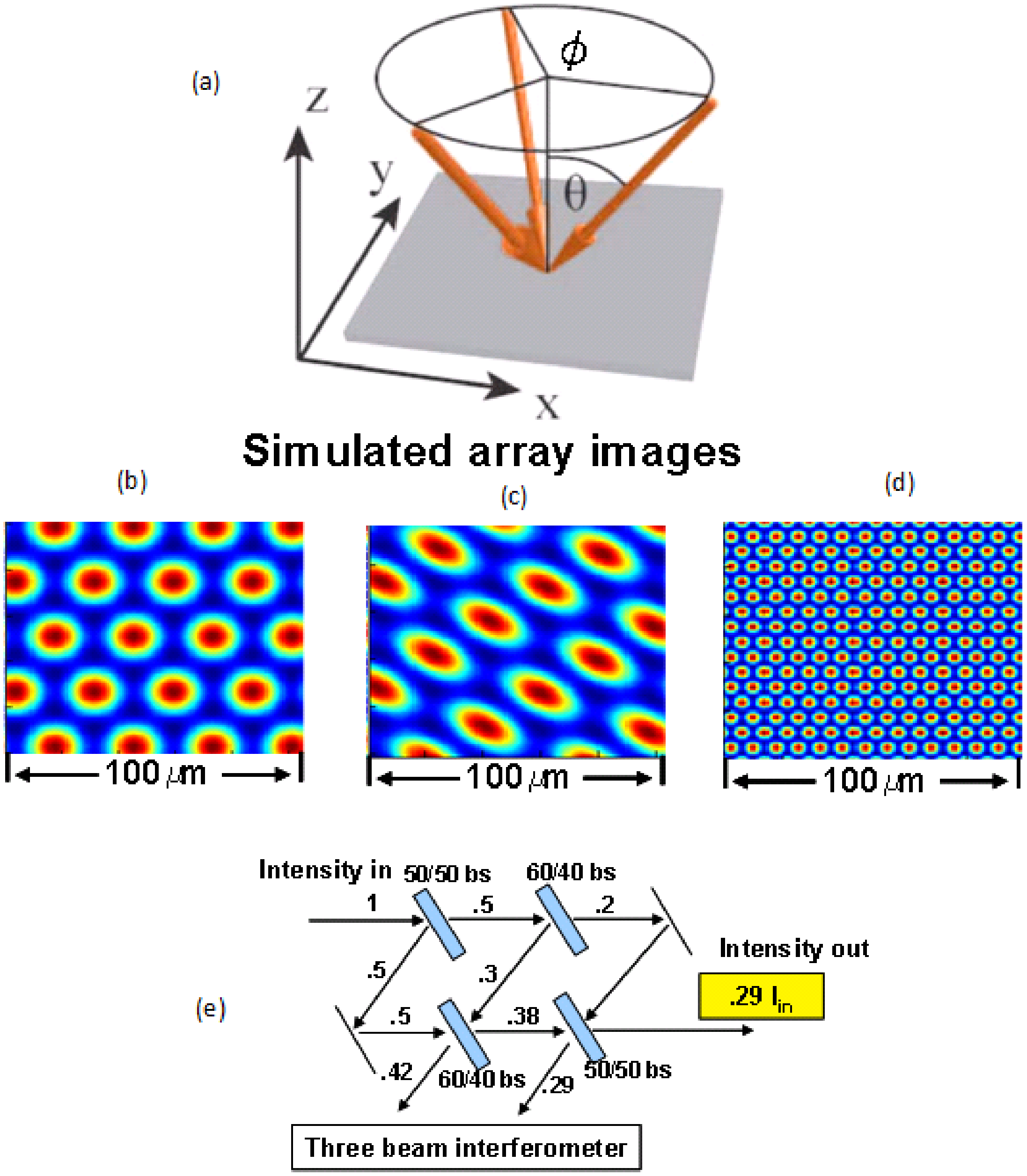

Figure 3: (a) Diagram of array generation using a three-beam interferometer. (b)-(d) Examples of simulated output light intensity. (e) Optical layout of the interferometer using 50/50 and 60/40 beam splitters. The top two split the beam and the bottom two recombine each beam to interfere. Notice the lost light through the recombiners. This accounts for the lower output intensity in the interferometer than the wire mesh.

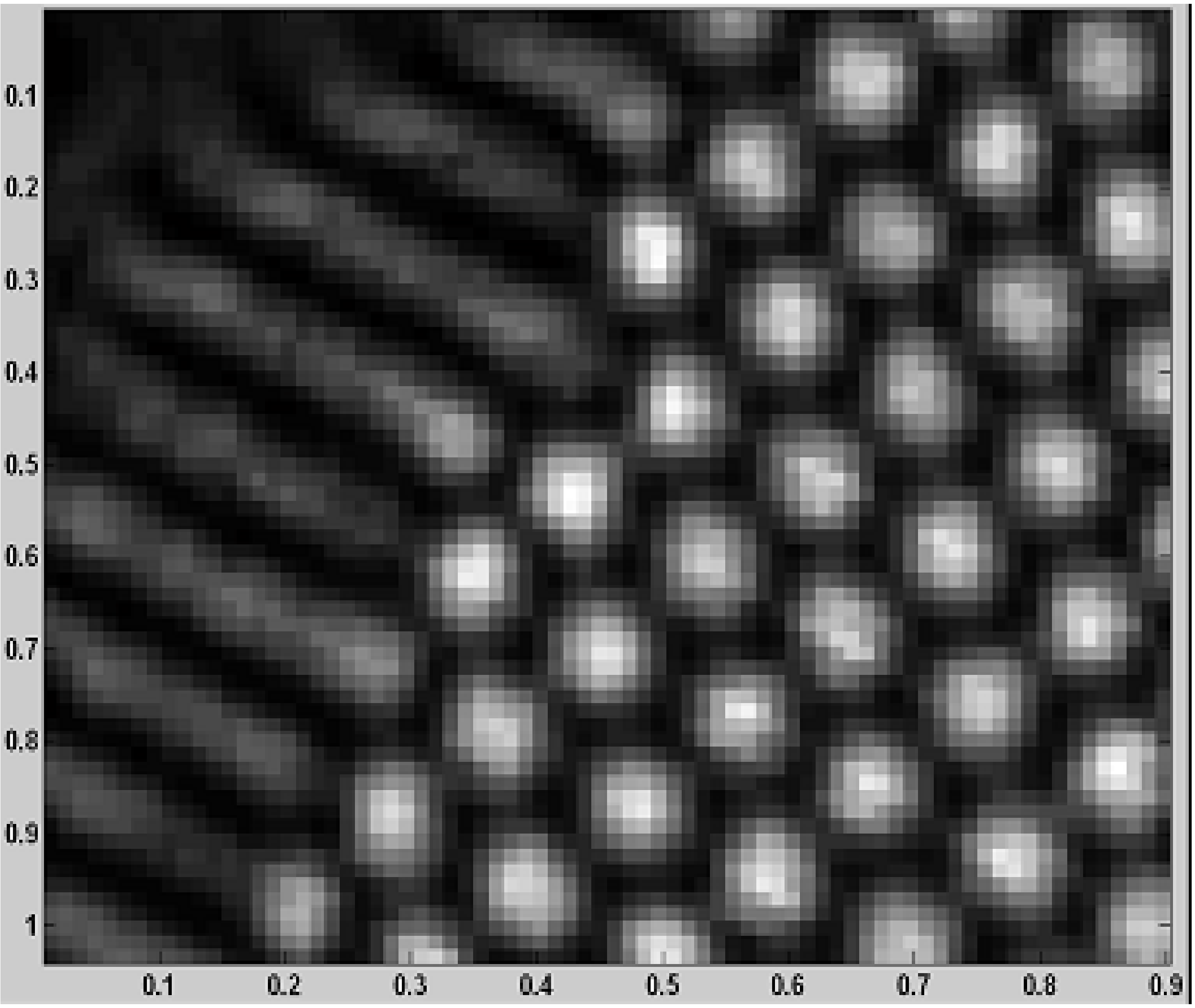

Figure 4: Grid image from three beam interference. The beam lines on the left of the image represent two beam interference fringes, due to the third beam not being combined completely. Very good contrast of 89% is seen around the grid points, usable for image processing.

3. Conclusion

The diffraction caused by the Talbot effect of a physical grid has been shown to match expected values. This level of diffraction adds a well defined and significant limitation to the frequency of a grid usable in GIR. The use of a grid with a spacing too small will result in unusable images.

A three beam interferometer has been constructed to form an array of hexagonal dots through interference. Because there is no diffraction, the hexagonal array is distinct and resolvable along the entire optical axis. The ability to precisely control the spacing and orientation of the grid has been demonstrated. Using this interferometer could allow the production of arrays of much smaller spacing than what was available using physical grids.

References

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