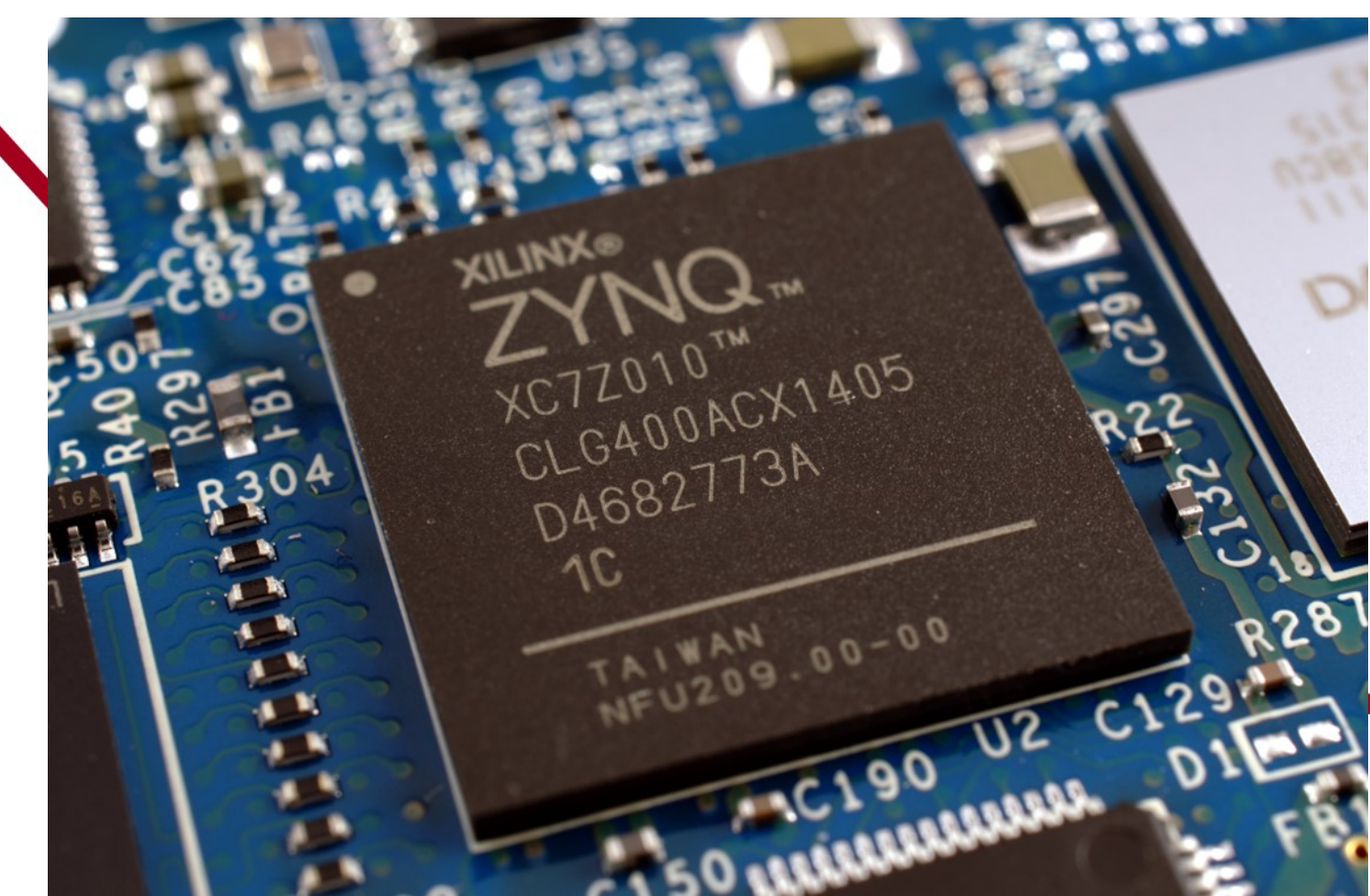


Experiments with FPGA Hardware for Acceleration of LCLS Image Processing



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Introduction

Image processing is an indispensable part of analyzing LCLS data, examples being XTCAV data analysis or wavefront sensing. For wavefront sensing, an essential calculation is the Fast Fourier Transform, or FFT. With a conventional CPU, the FFT requires an expensive amount of time when dealing with the particularly fine images taken from the megapixel CCD cameras.

Here we present one attempt to offload the FFT calculations from the CPU to the FPGA, i.e. hardware acceleration.

Keywords: Image Processing, FPGA, Fast Fourier Transform, hardware, cameras

Research

A Field Programmable Gate Array (FPGA) is a semiconductor device comprised of vast amount of logic blocks and dedicated circuits like multipliers and digital signal processing units (DSP), with interconnections between them. Through configurations of the interconnections, an FPGA can be programmed to perform different tasks, with native parallelization and pipelining.

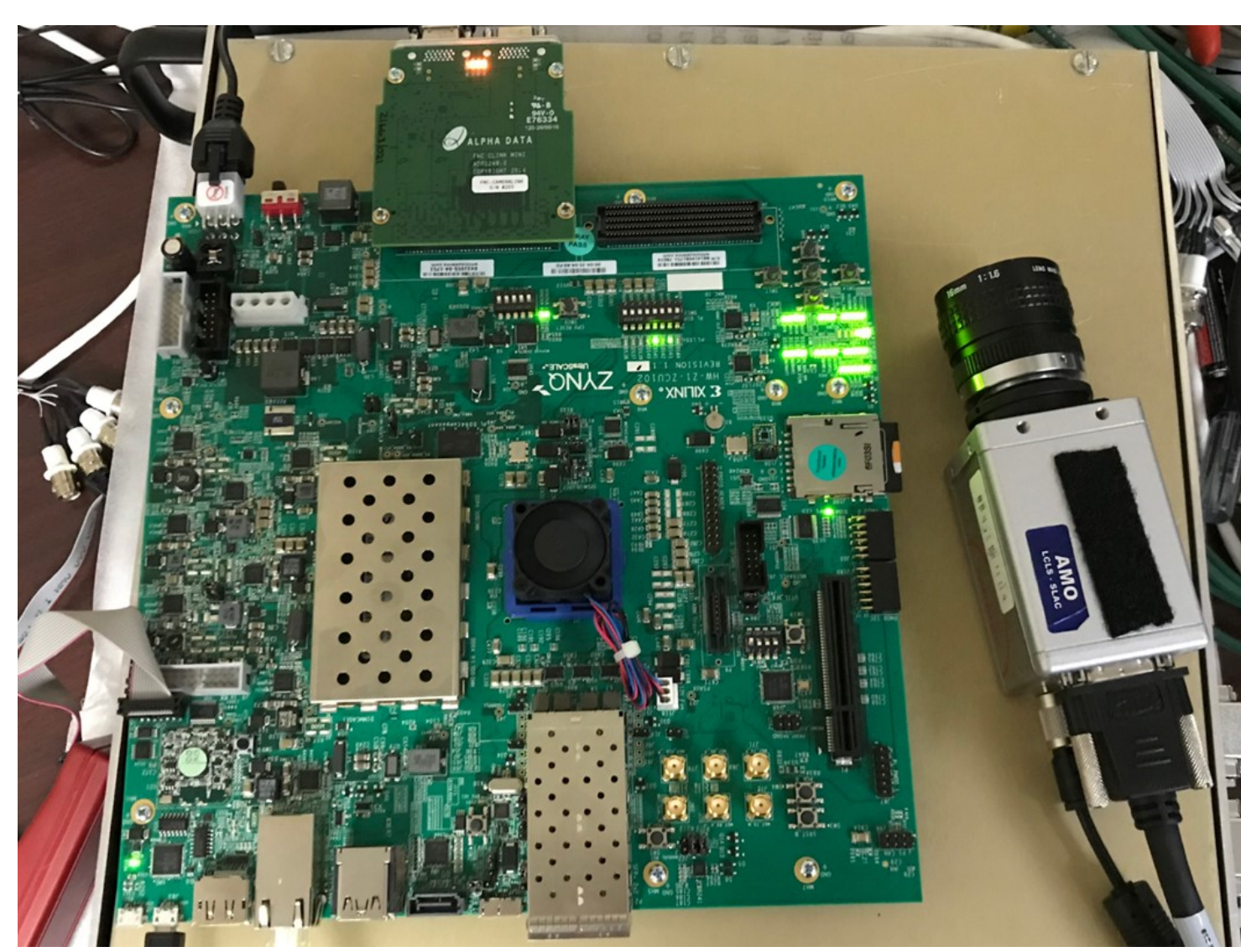


Fig 1. Xilinx development board zcu102 connected with an OPAL-1000 camera

For this experiment, we target a development board from Xilinx, the zcu102 (see fig 1), and went through the following procedure:

1. Capture a test pattern with the OPAL (Figure 1)
2. Perform 2D FFT with MATLAB (Figure 3)
3. Perform 2D FFT with a C-model package. Xilinx provides this for users to simulate/predict the FPGA's FFT performance (Figure 4)
4. Perform the 2D FFT on the actual FPGA on the zcu102 board (Fig 4)

The 2D FFT

The formula for the 2D FFT is as follows:

$$F(u) = \frac{1}{N} \sum_{x=0}^{N-1} \sum_{y=0}^{N-1} f(x,y) e^{-j2\pi(xu+vy)/N}$$

It is 1D FFT on each individual row, and then 1D FFT on the resulting columns.

Results

Taking a simple dark square printed on a piece of paper, the board captured a 1024 x 1024 pixel image with the attached OPAL-1000 camera. We then ran the resulting numbers with the MATLAB FFT function, to get the target structure.

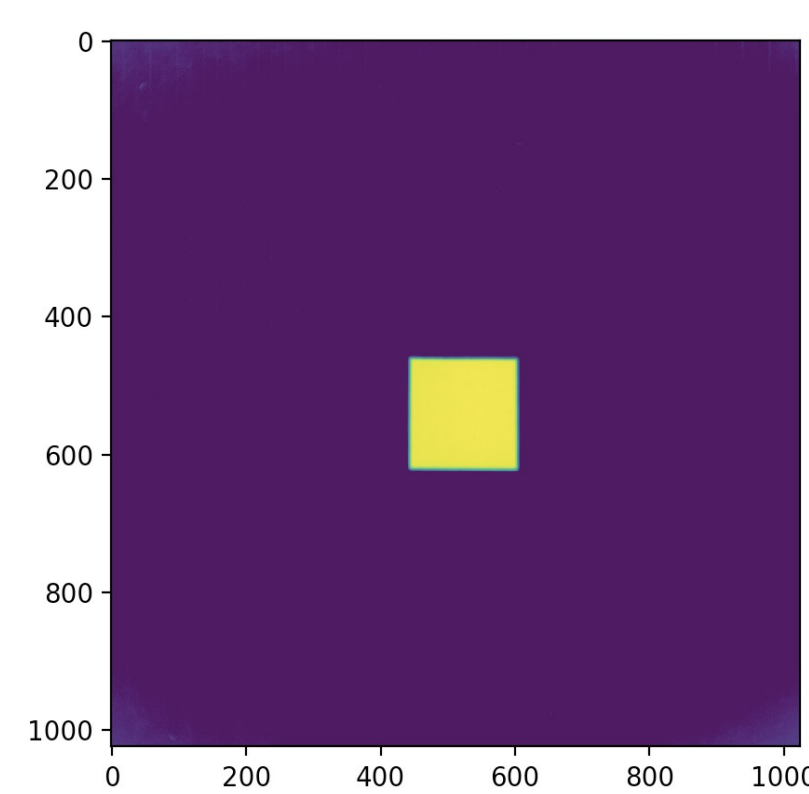


Fig 2. Original square.

We then created a C program to simulate FFT using the Xilinx package. Running the C code, we created the same FFT procedure on this dark square. The results are shown below:

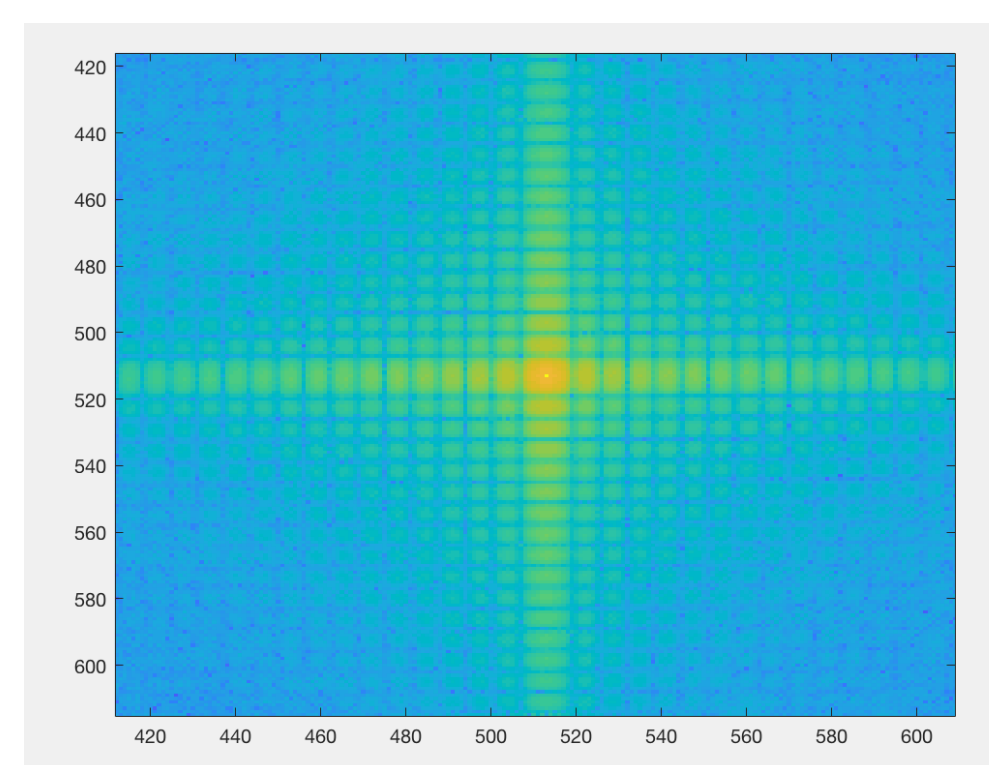


Fig 3. MATLAB FFT result in the frequency domain

As can be seen, there is both this receding cross-shaped structure with the MATLAB and C simulation procedures. It appears empirically that the Xilinx FFT package produces a correct calculation. With this knowledge, it would be feasible to test the FFT package using the FPGA hardware itself.

Processing the FFT on the actual FPGA board, the following results were obtained.

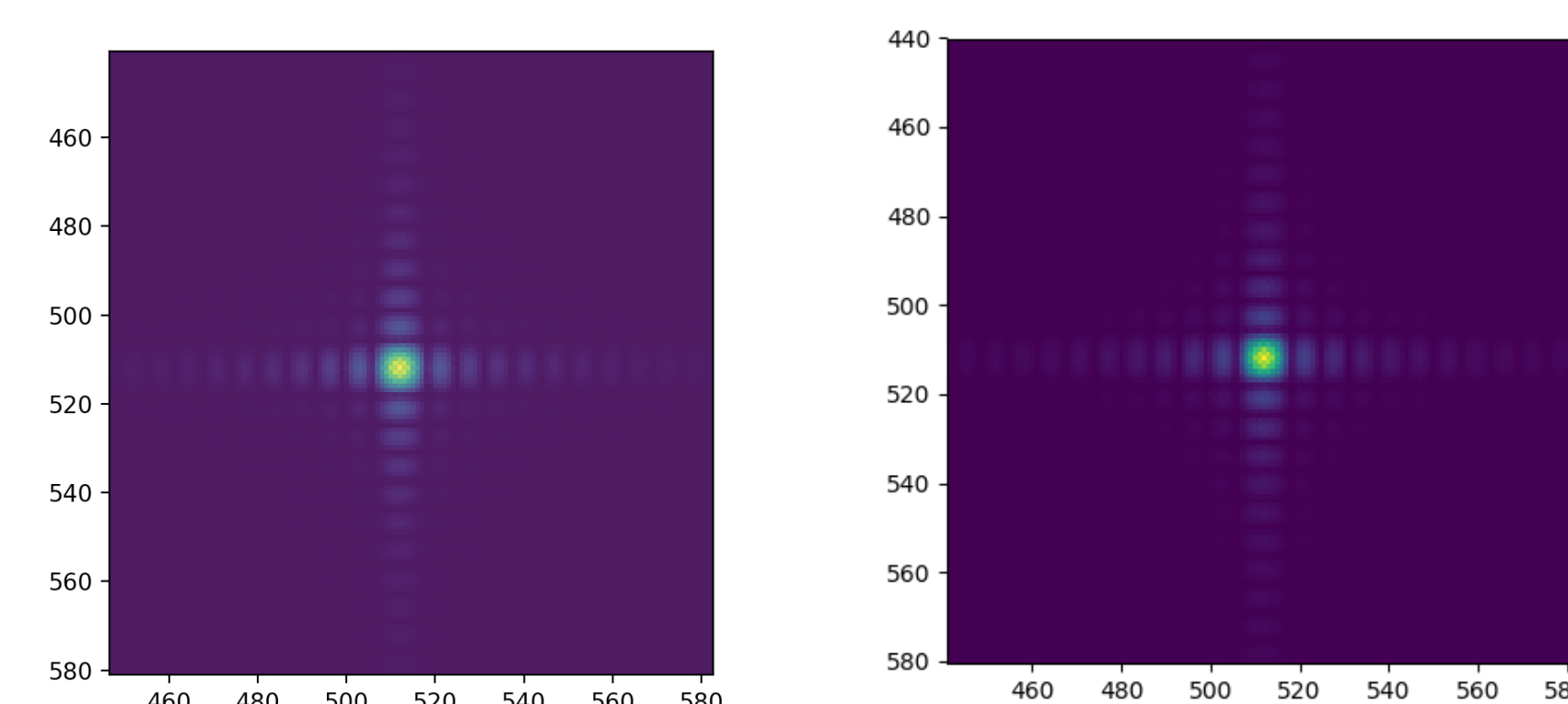


Fig 4. Left- Zoomed image of Xilinx C FFT result Right - FPGA Processor result

As can be seen, the FPGA processing produces strikingly similar 2D FFT patterns. This processor is seen capable of reproducing traditional calculations quite accurately

Applications

Example: Fourier Optics propagation

We applied Xilinx FFT package to create a Fourier Optics wavefront propagation tool. We have found the results completely matched those from an already established MATLAB procedure.

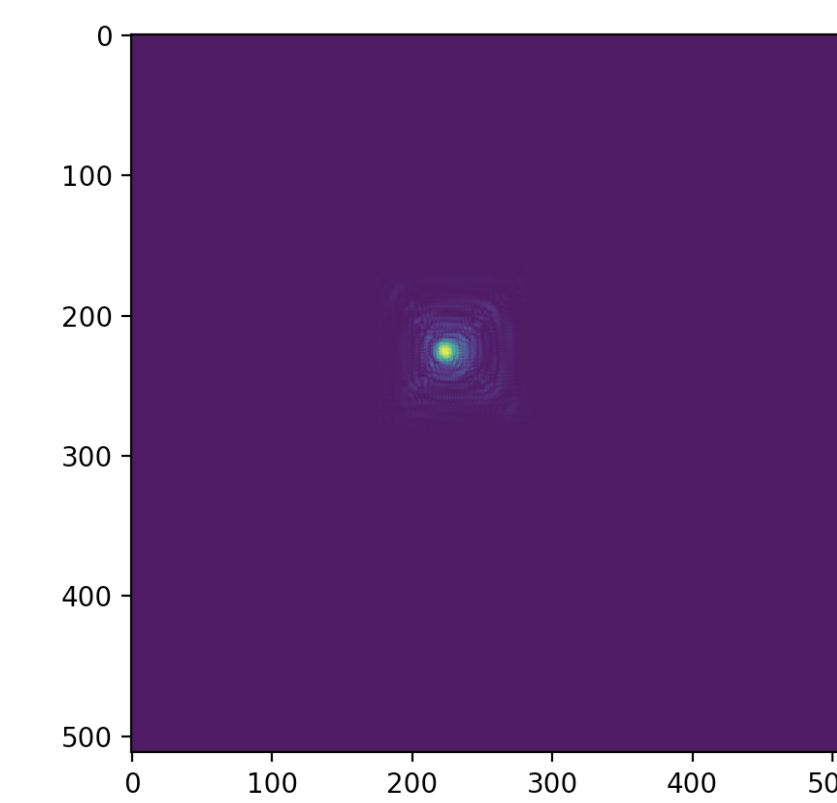


Fig 1. 1024 * 1024 pixel grid. The input data represents LCLS X-ray field at 1400 eV, at the undulator exit, derived from a start to end simulations (courtesy of Yuantao Ding)

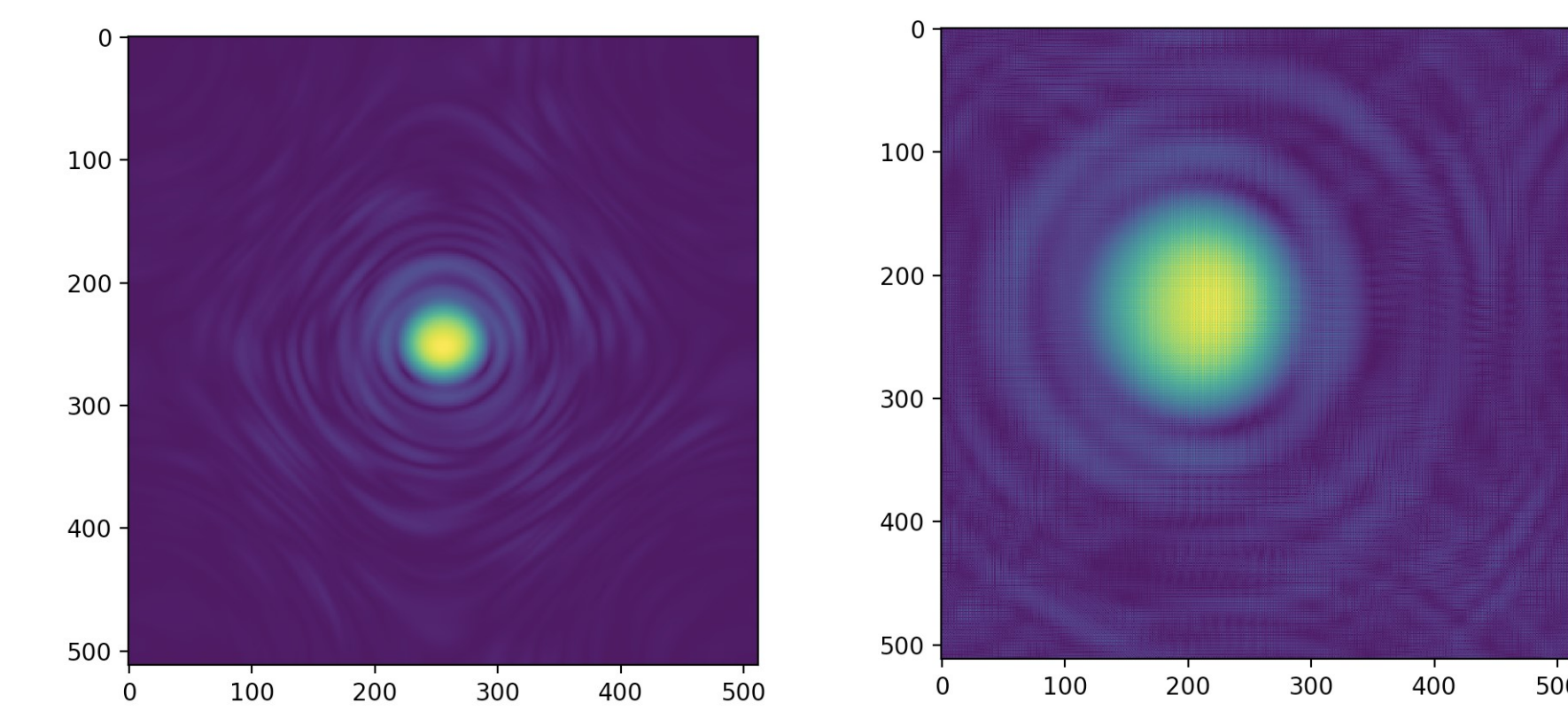


Fig 5. Left - FFT of the input data. Right - Propagation of the field by 70 m to the FEE Direct imager position

Conclusions

We were able to capture images and process the FFT with the FPGA, and received a 2x processing acceleration. However, this project is still in progress and so there are much more refinements to be made.

FPGAs can be extrapolated to any imaginable utility or function, hence the name "field programmable". FPGAs are useful in machine learning, digital signal processing, surgical systems and more. One notable recent development is actually with self-driving cars, where FPGAs allow for real-time, flexible clocked image and video analysis. Overall, the FPGA has vast potential where processing needs are high.

Acknowledgments

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