Small Form Factor Full Parallax Tiled Light Field Display

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ABSTRACT

With the recent introduction of Ostendo's Quantum Photonic Imager (QPI) display technology, a very small pixel pitch, emissive display with high brightness and low power consumption became available. We used QPI's to create a high performance light field display tiles with a very small form factor. Using 8 of these QPI light field displays tiled in a 4x2 array we created a tiled full parallax light field display. Each individual light field display tile combines custom designed micro lens array layers with monochrome green QPIs. Each of the light field display tiles can address 1000 x 800 pixels placed under an array of 20 x 16 lenslets with 500 µm diameters. The light field display tiles are placed with small gaps to create a tiled display of approximately 46 mm (W) x 17 mm (H) x 2 mm (D) in mechanical dimensions. The prototype tiled full parallax light field display demonstrates small form factor, high resolution and focus cues.

Keywords: light field display, tiled light field display, QPI, full parallax

1. INTRODUCTION

Human visual system makes sense of the environment by sampling from the infinite amount of light rays that exist in the environment. The ultimate display should be able to discretize the light rays that exist in an environment and present them to the human visual system in a manner indistinguishable from reality. Being indistinguishable from reality would mean that the images displayed by an ultimate display would have full parallax, correct color reproduction, high dynamic range, correct depth cues (triangulation, perspective, shading, etc.), correct focus and blur cues (no vergence-accommodation conflict (VAC), no discomfort or fatigue), no temporal artifacts (flicker, judder, motion blur, edge banding etc.), see [1] and [2]. Currently such an ultimate display does not exist; however, research on light field displays, super multi view displays, integral imaging displays and digital holography is slowly inching toward addressing the volumetric nature of the ultimate display. Attempts at eliminating the discomfort in 3D displays were studied using the super multi view method [3]; however, recent research has suggested that having horizontal only parallax would not be able to address the discomfort issue fully [4]. A full parallax super multi view display that can present sufficiently dense amount of light rays can be the solution to the volumetric nature of the ultimate display.

Full parallax displays were previously considered not practical due to the large amount of data bandwidth required to feed the display and highly complex system design requirements to integrate existing displays into a manageable form factor. New solutions to rendering and compressing light field data have been introduced in [6] and [7]. A quick survey of the existing light field display technologies show that the hardware volume of a light field display can be in the range of approximately 0.5 m^3 to 3.6 m^3, see [8] - [15]. The main reason for the large hardware volume of the light field displays is the inability to tile the existing display technology in a compact form factor. Small pixel pitch, emissive displays with high brightness and low power consumption are required to enable new light field display designs with smaller form factors. A new display technology that meets this description is Ostendo's Quantum Photonic Imager (QPI) display device. QPI is an emissive display technology with 10 µm or less pitch pixels, high brightness and low power consumption, [5].

We created a very small form factor full parallax tiled light field display using a 4x2 array of light field display tiles. Each individual display tile makes use of the QPI. We combined custom designed micro lens array layers with monochrome green QPIs to create very small form factor light field display tiles. Each of these small light field display tiles can address 1000 x 800 pixels placed under an array of 20 x 16 micro lenses each with 500 µm in diameter.

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These small light field displays are tiled with small gaps to create a tiled display of approximately 46 mm (W) x 17 mm (H) x 2 mm (D) in mechanical dimensions. The tiled display addresses total of 6.4 mega pixels with an array of 80 x 32 micro lenses to create a light field with more than 120 mm depth of field, 34° viewing angle at 60 Hz refresh rate. To our knowledge this is the first full parallax light field display with such a small form factor and large depth of field.

2. QPI

The QPI is a 3D-IC semiconductor device comprising a high density array of digitally addressable micro-size pixels [5]. Each pixel (see Figure 1) consists of a vertical stack of multiple Light Emitting Diode (LED) layers, each of which generates light of a different primary (Red-Green-Blue) color. Three dimensional integrated circuit (3D-IC) techniques are used to meld the patterned photonic material to an equivalently patterned CMOS digital logic comprising an array of the pixels control circuits. The result is an array of digitally addressable "Smart" pixels each comprising its own light generating material as well as all of the needed logic to control it. The QPI architecture alleviates the drawbacks of existing micro-display devices in particular those related to power efficiency, compactness and cost. Small pixel pitch of the QPI combined with its high brightness makes QPI an ideal candidate for full parallax light field displays.

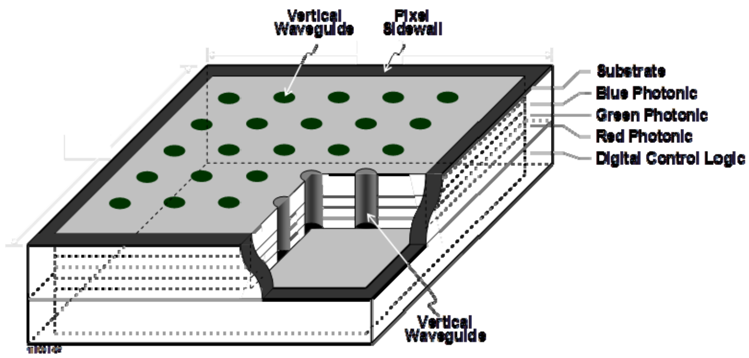

Figure 1: QPI Device Architecture, Structure of a single QPI Pixel

3. 3D QPI TILE

One of the key innovations of the QPI technology is its ability to integrate the emission of multiple wavelengths from the surface of each pixel with all the wavelengths sharing the same pixel aperture. This capability is an important aspect of the QPI design architecture in which light is extracted vertically from the stack multiple photonic layers through coupling into the same set vertical waveguides that extend the height of the photonic layers stack. Since all color emits from the same QPI pixel aperture, when used as a base display layer in a micro lens based light field display QPI would eliminate the color moiré observed in other displays that utilize spatially arranged color sub-pixels.

Before creating the 4x2 tiled light field display, we first created a single tile, called 3D QPI, and observed the images presented on it. Monochrome green QPI with 10 µm pixel pitch was chosen as the base layer for the 3D QPI. To satisfy the super multi view condition we designed a custom micro lens array with 500 µm micro lens pitch and 34° field of view (FOV). This allowed an array of 50x50 QPI pixels to be placed under each micro lens and share the FOV, creating an angular pitch of 0.68°. The lens array was manufactured in Ostendo Nano Technology Laboratory and glued to the QPI surface with careful alignment and focusing of the lens array. The viewing distance for the 3D QPI was set at ≥30 cm. Figure 2 shows a 3D QPI and a full parallax image shown on it from different perspectives.

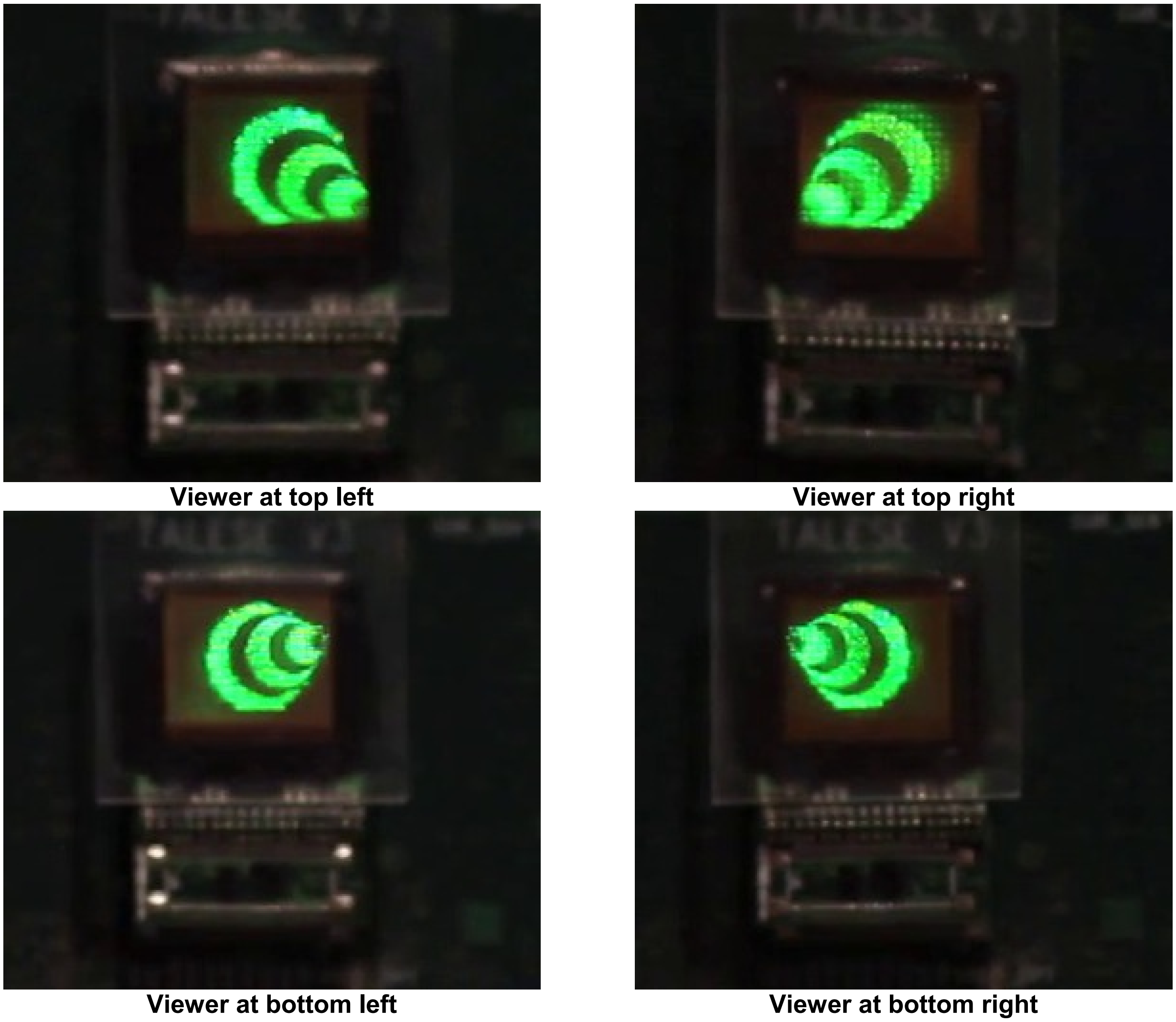

Figure 2: 3D QPI and a full parallax cone image pictured from different viewing locations.

4. SYSTEM DESIGN

The 4x2 tiled light field display system consists of a rendering computer with GPUs, an interface processor for supplying image data and power, two array boards for accurate placement of the tiles and 8x 3D QPI tiles.

4.1 Array Board Design

We decided to use a 4x2 array of 3D QPI tiles to create display with 2.5:1 aspect ratio. This aspect ratio allowed us to see wider full parallax images while still being easy to prototype. To increase the robustness of the system we decided to create two 4x1 array boards. In case of a human error or component failure in fabrication, this allowed replacing of the 4x1 array board without sacrificing too many good components.

Figure 3 shows a perspective view of the 4x2 tiled light field display concept using two 4x1 array boards. The two identical boards are placed next to each other with the 3D QPI tiles placed as close as possible.

To populate each of the 4x1 array boards we first attached the QPIs to array board. Each QPI was attached on the array board using pick and place machinery with a placement accuracy of < 5 μm. After the attachment of the QPIs, the size of the active display for a single array board was 46.3 mm in horizontal and 8 mm in vertical. Within this area, there are 3x 2.1 mm horizontal inactive regions. When the two boards were combined together as shown in Figure 3, the size of the active area was set at 46.3 mm in horizontal and 16.96 mm in vertical with 0.96 mm vertical gap between the active regions of the two boards. The thickness of the display measured from the top of the micro lens array to the top of the array board is approximately 2 mm.

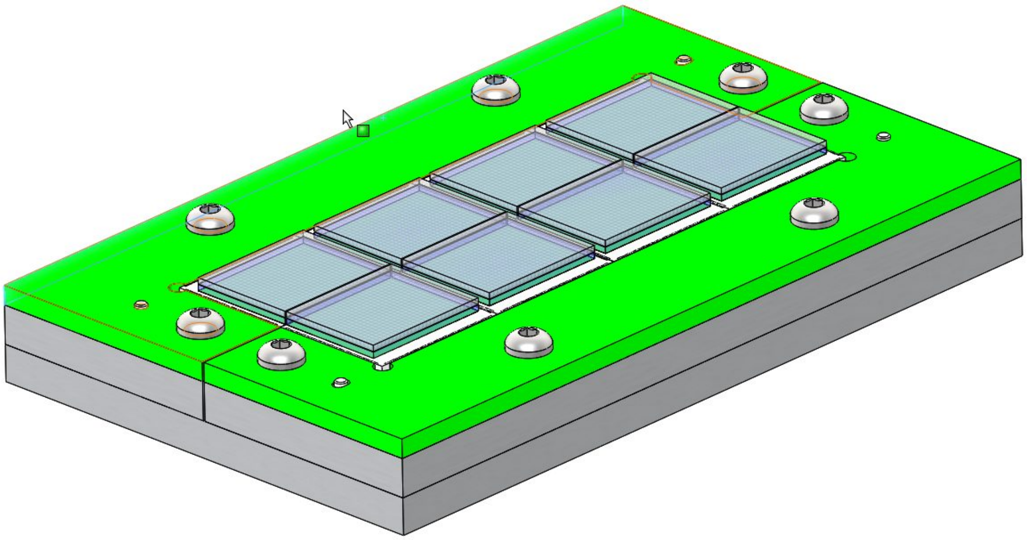

Figure 3: Perspective view of 4x2 tiled light filed display concept showing two array boards

4.2 Alignment and Gluing of the Micro Lens Arrays

To reduce the digital calibration steps as much as possible, we created a robust micro lens alignment, focusing and gluing procedure. The micro lens arrays were manufactured with alignment marks that had their matching counterparts on the QPI device to eliminate yaw and x-y translation errors. Once the correct alignment was achieved in x-y plane, the micro lens array was translated in z direction to adjust its focus. In this display, we placed the QPI pixels at the back focal length of the micro lens array and created a focused display system. Once the desired focus was achieved we glued the micro lens array to the QPI device. Figure 4 shows a fully assembled 4x2 tiled light field display.

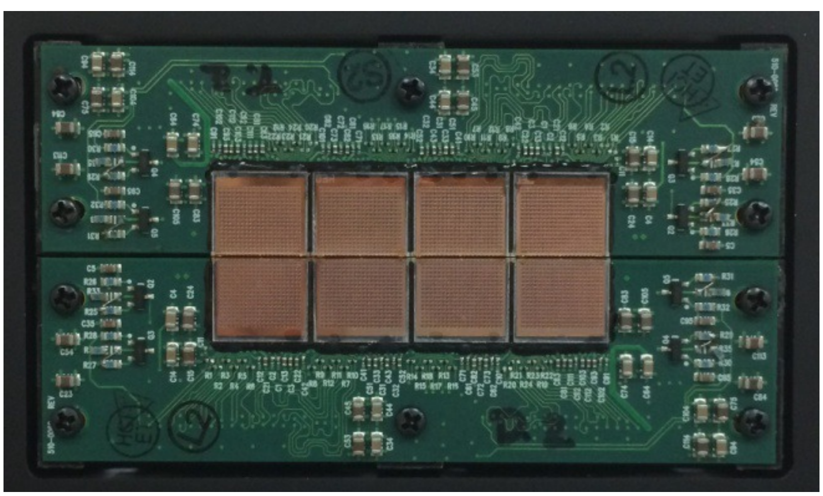

Figure 4: Fully assembled 4x2 tiled light field display

4.3 Rendering

The rendering for our tiled display was done on a computer with Intel Core i7-4960X CPU running at 3.6 GHz, with 16 GB RAM, and Windows 7, 64-bit operating system. We used 4x AMD FirePro v7900 GPUs with software synchronization to provide images to the display. Each GPU supplied an image for two tiles with the resolution of 1000 x 1600 pixels. This image was processed by the interface processor to relay 1000 x 800 pixel images to each tile.

For rendering the light field image, we adopted the dual frustum rendering method described in [16] to the modern GPU based rendering methods using DirectX 11. The images were rendered in real time and displayed at 60 Hz synchronously by each tile. The rendering software allows real time interaction using devices such as Xbox game controllers, mouse and keyboard.

5. CALIBRATION

Calibration was done offline and loaded into rendering software through parameter files. The three main calibration operations performed on the system were:

1. Luminance uniformity calibration
2. Micro lens array to QPI rotation (yaw) calibration
3. Micro lens array to QPI translation (x-y plane only) calibration

We did not have to worry about tile placement tolerances, roll and tilt error between the micro lens array and the QPI, translation in z (or focus) errors due to the robustness of our processes with respect to these errors. Even though yaw and x-y translation were minimized during the micro lens alignment process, the calibration was necessary to further fine tune the system.

5.1 Luminance uniformity calibration

In a tiled display system there a two types of luminance uniformity calibration necessary, local and global calibration. Local or intra-tile calibration means the luminance non-uniformities inside a tile are corrected. Global or inter-tile calibration means the luminance non-uniformities from tile to tile are corrected.

We prepared for local calibration by making provisions in our rendering software to make local corrections in each QPI image. Eventually we did not have to do it because the image quality after global calibration looked good enough.

We performed global calibration by measuring the luminance of each QPI with a spectroradiometer and adjusting the luminance of each QPI by adjusting its input current.

5.2 Micro lens array to QPI translation (x-y plane) calibration

In the display each pixel is assigned to a specific micro lens. To determine the alignment of micro lenses to the group of lenses they are supposed to work with, we used Eldim VCMaster3D device [17]. VCMaster3D device is an angular measurement device with high angular pitch accuracy. Collimated light rays generated by each pixel in the 3D QPI tile maps to a specific location in the angular measurement provided by the device. In simplest terms, while our display converts pixel location to direction, VCMaster3D device converts direction to pixel location. Figure 5 shows the angular measurement for light emitted by a single micro lens in the 3D QPI tile. As shown in Figure 5, 50 x 50 array of directional light rays, as indicated by the bright spots on the picture, are distributed within ±20°. These bright spots correspond to pixels under a micro lens. The picture shows that the pixel array is not centered; there is a one pixel shift to the top and one pixel shift to the right. By inputting these values to the software we fix the misalignment of the micro lens array with the pixel array.

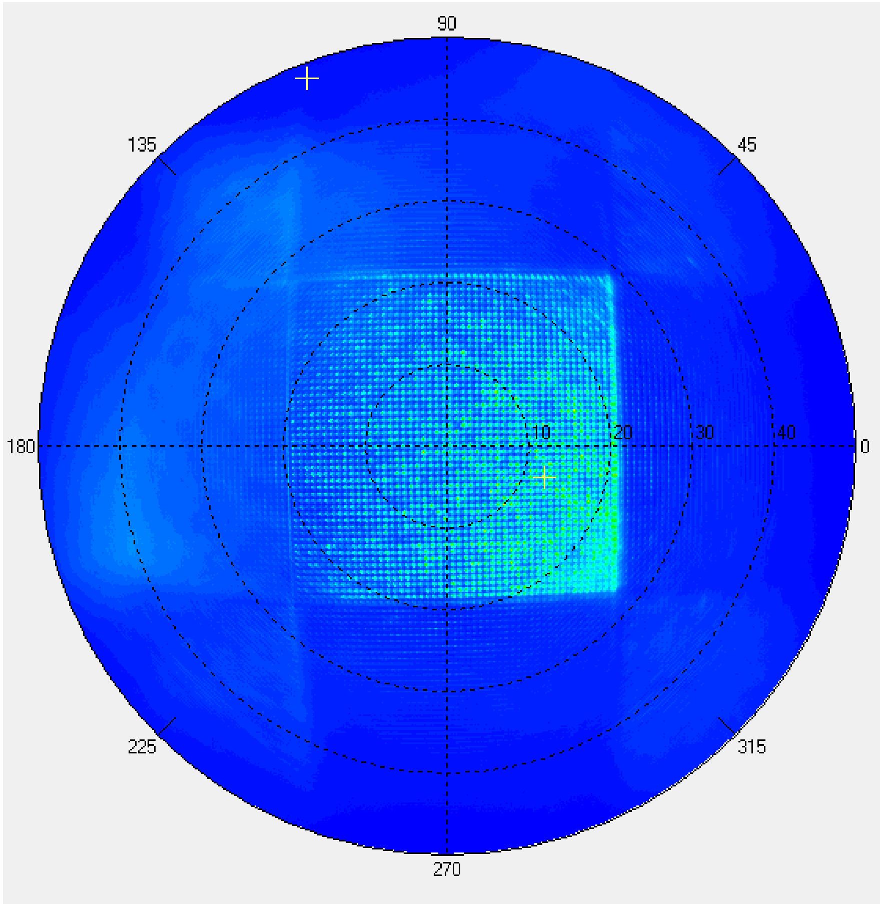

Figure 5: A sample anglet image taken by the VCMaster3D device

5.3 Micro lens array to QPI rotation (yaw) calibration

To perform yaw calibration we displayed horizontal and vertical lines on each tile, recorded the displayed images with a camera and analyzed the results. Our analysis revealed that some tiles had micro lens array rotation of $\leq 0.1°$. The calculated value for each tile was input into the rendering software as a calibration parameter.

5.4 Calibration Result

Figure 6 shows horizontal and vertical lines going through the center of each tile before calibration and after calibration. As shown by the figure, luminance uniformity, rotation and translation errors were fixed by the calibration operations.

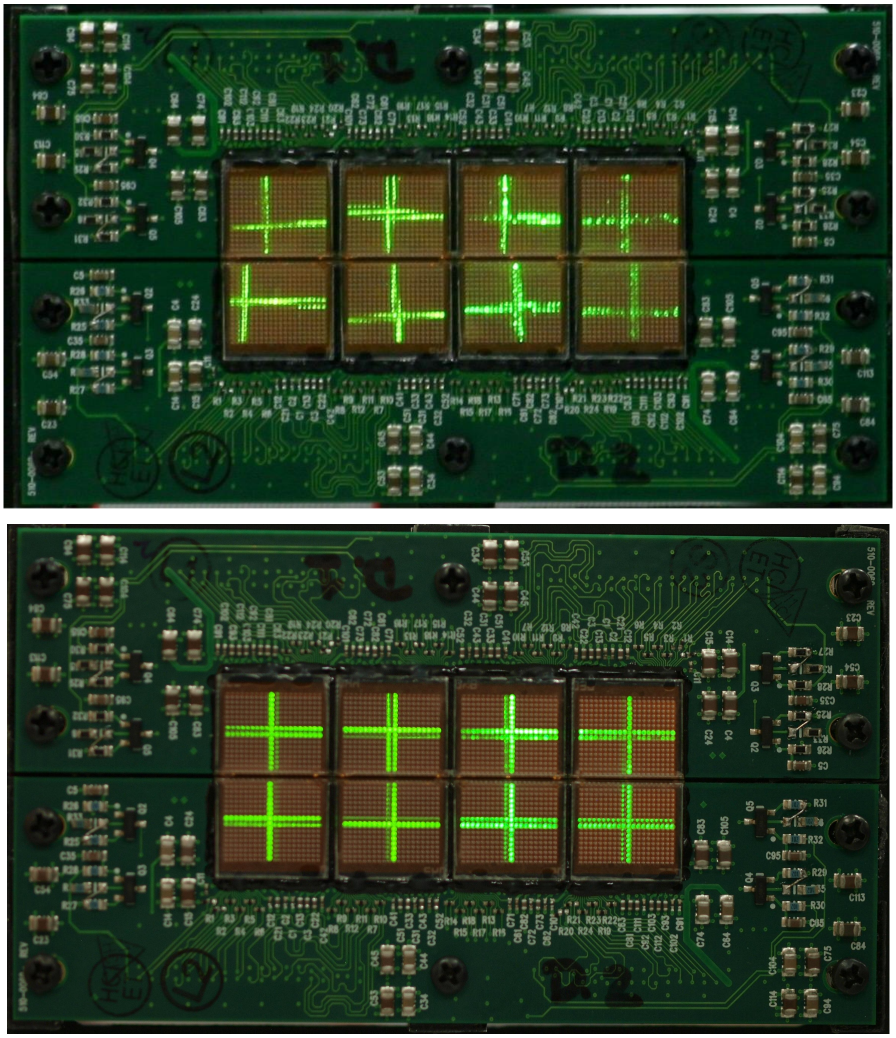

Figure 6: Before calibration (top picture) and after calibration (bottom picture)

6. RESULTS

Figure 7 shows the horizontal and vertical parallax capability of the display. Horizontal parallax is demonstrated by the pictures at the top and vertical parallax is demonstrated by the pictures at the bottom. To take the horizontal parallax pictures we rotated the display physically while the camera was stationary. To take the vertical parallax pictures we translated the camera vertically using the tripod.

Figure 8 shows the depth of field displayed by our 4x2 tiled light field display. In Figure 8 a camera was able to focus on the light field images generated away from the display plane by help of a diffusing screen. The diffusing screen was moved from 10 mm to 60 mm away from the display as indicated by the images generated by the display. As seen by the pictures the images displayed by the 4x2 tiled light field display are readable up to 60 mm away from the display surface. Since this is a focused display system, the same is also true for images that are displayed behind the display plane.

Figure 9 shows the camera focusing on the displayed light field images directly without the help of a diffusing screen. The three cubes displayed by the light field are placed in front of the display plane (top picture), crossing the display plane (middle picture) and behind the display plane (bottom picture). As seen in the figure, as the camera focuses on one cube the other cubes get blurry which demonstrates appropriate focus cues generated by the display.

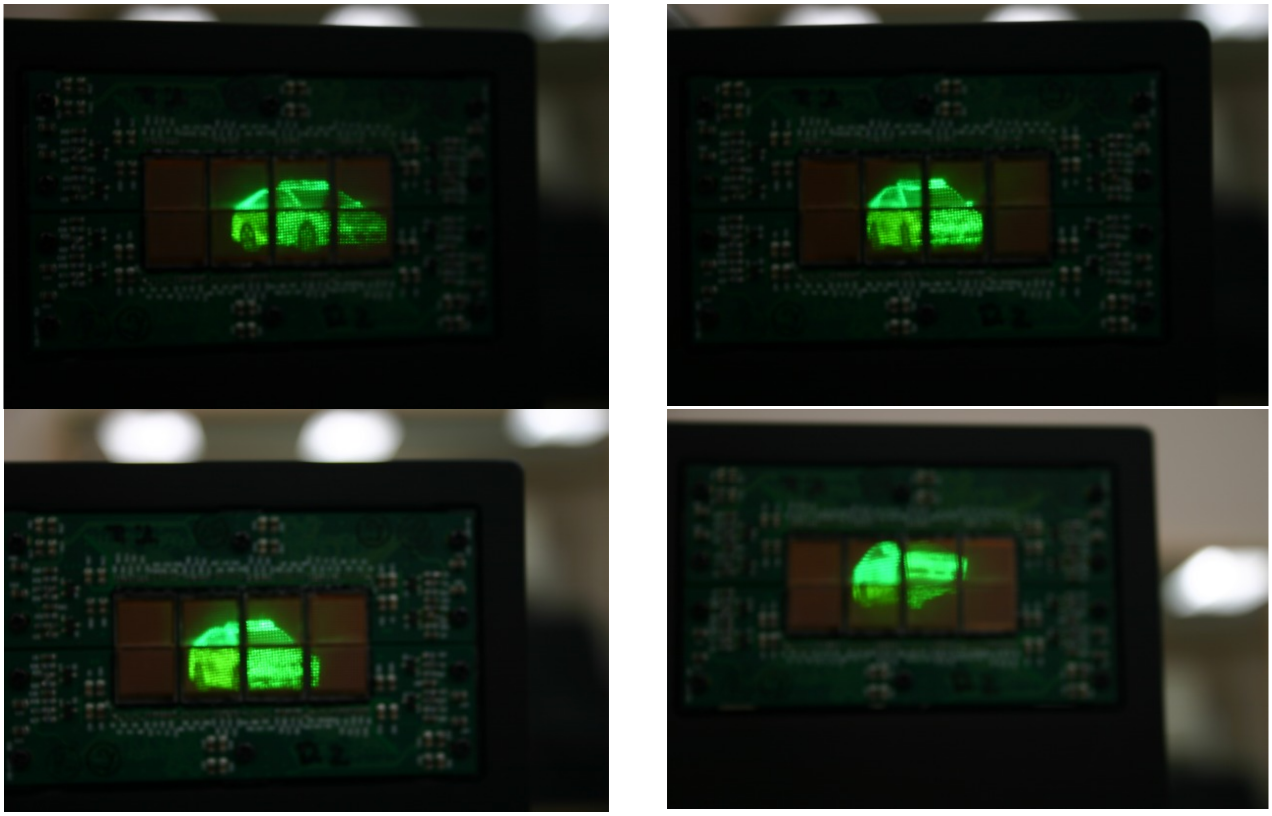

Figure 7: Horizontal parallax (top pictures) and vertical parallax (bottom pictures) demonstrated by the display.

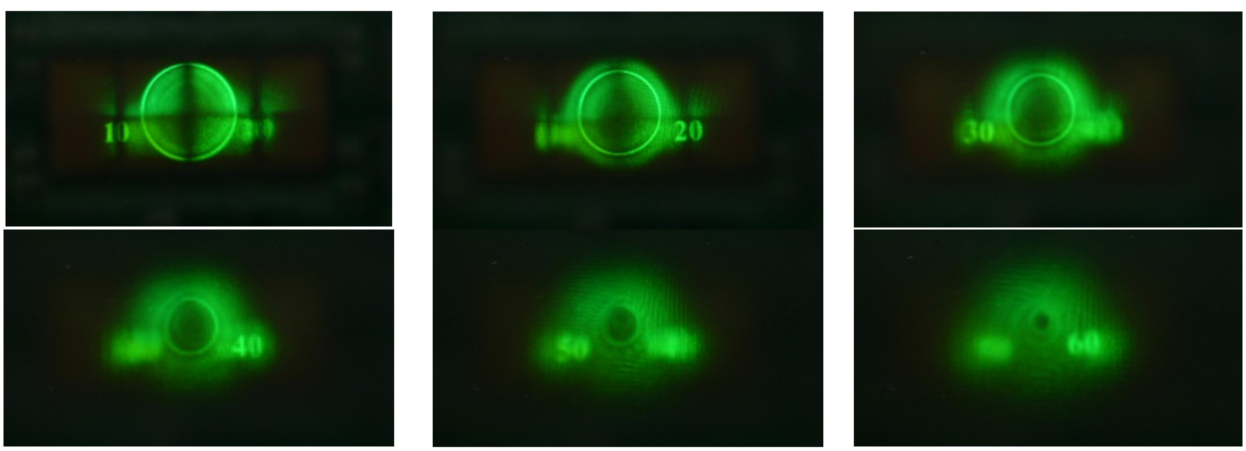

Figure 8: Front depth range and focus capability of the 4x2 tiled light field display. The image in the top left shows an all focused picture. The other images show focus away from the display from 10 mm to 60 mm in front of the display plane

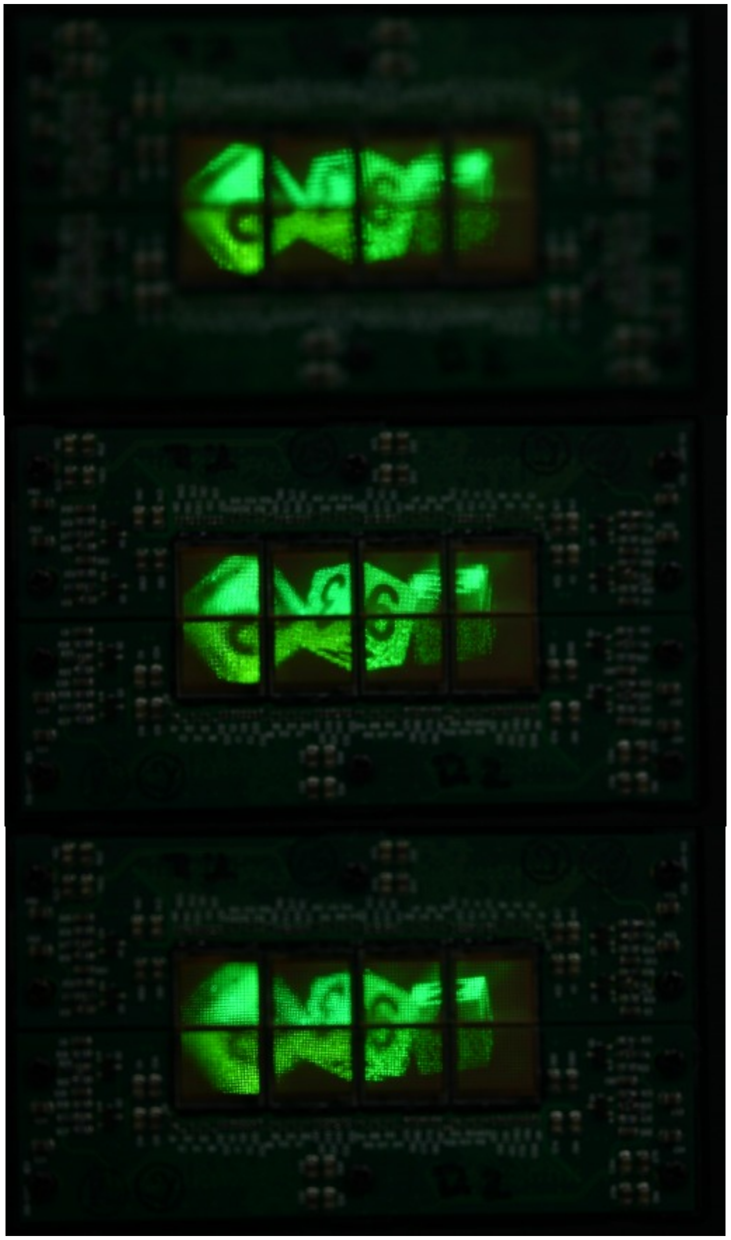

Figure 9: Cube images generated by the 4x2 tiled display device. The focus of the camera was set at front cube (top picture), middle cube (middle picture) and the back cube (bottom picture).

7. CONCLUSIONS AND FUTURE WORK

We built a monochrome compact full parallax tiled light field display that has a large depth of field. The display creates images that are focusable by a digital camera and exhibits text readability up to 60 mm away from the display surface in both in front and behind the display plane.

In future work, we plan to demonstrate the color advantage of the QPI displays by creating a full color and full parallax tiled light field display with a larger size and without any color moiré.

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