Angle Sensitive Pixels in CMOS for Light-Field Imaging

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Overview

- New class of pixel-scale structures - "Angle sensitive pixels" (ASPs)
- Measure intensity <u>and</u> incident angle of light
- Compatible with CMOS processes with no additional post processing
- Low cost manufacturing in existing contract facilities (i.e. TSMC)
- Compared to standard imager pixels, ASPs capture much more information about the light they receive
- Applications in low-cost biomedical assays, digital photography and various sensors

Target Applications

Traditional solid state image sensors use pixels which measure the intensity of incident light. However, incident angle contains significant information about three-dimensional structure, which could be used to extract 3-D structure in both lens-based and lens-less systems.

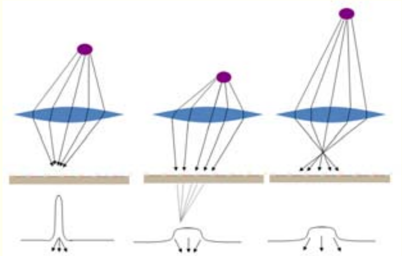

Figure 1: In a lens system (i.e. camera), angle information informs us about focal depth.

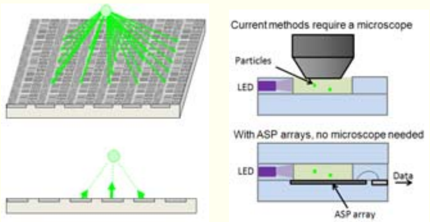

Figure 2: In a lens-less system, angle information allows 3D localization, of luminous objects, such as tagged cells. Thus an ASP array could replace the microscope in many applications

Principle of Operation

The demonstrated ASP relies on the Talbot effect. Light incident on a diffraction grating forms periodic intensity patterns (called self-images) behind the grating.

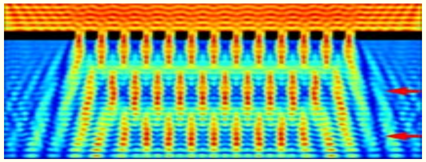

Figure 3: The Talbot effect. Periodic intensity patterns occur at specific depths (red arrows)

These periodic intensity patterns shift laterally in response to changes in incident angle. A second diffraction grating, or analyzer grating, measures these shifts, and so incident angle, by alternately blocking or passing the self-images . A large photo detector below the analyzer grating measures the total light flux.

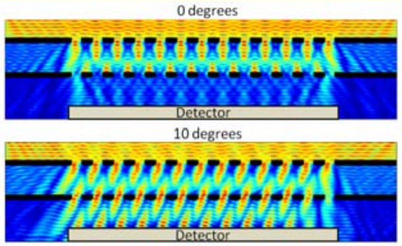

Figure 4: Measuring angle, using an analyzer grating to block or pass self-images.

CMOS Implementation: Easy to manufacture!

The proposed structure can be produced in a typical CMOS process, such as commercially available from TSMC. Metal wires form the gratings, while silicon structures implement the photo detector.

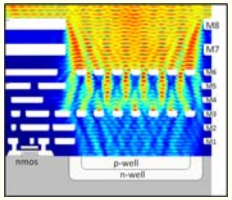

Figure 5: Example cross section in CMOS

Prototype ASP array

A full ASP needs several distinct structures with unique offsets between diffraction and analyzer gratings to distinguish changes in angle from changes in intensity. Our current designs use four vertical and four horizontal sensor structures.

We designed a small array of 64 ASPs, fabricated in a 130nm digital CMOS process.

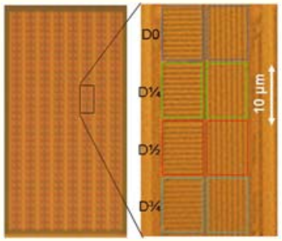

Figure 6: Microphotograph of manufactured 64 ASP array, with magnified view of a single ASP.

The manufactured ASP demonstrated the desired angle sensitivity. The outputs are sinusoidal curves where I is intensity and θ is incident angle.

$$V_0 = I_0(1 - m\cos(b\theta))F(\theta)$$
$$V_{1/4} = I_0(1 + m\sin(b\theta))F(\theta)$$
$$V_{1/2} = I_0(1 + m\cos(b\theta))F(\theta)$$
$$V_{3/4} = I_0(1 - m\sin(b\theta))F(\theta)$$

For the characterized device, m=0.7 and b=15.

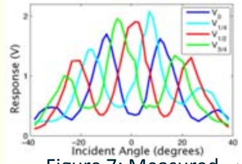

Figure 7: Measured response of the ASP

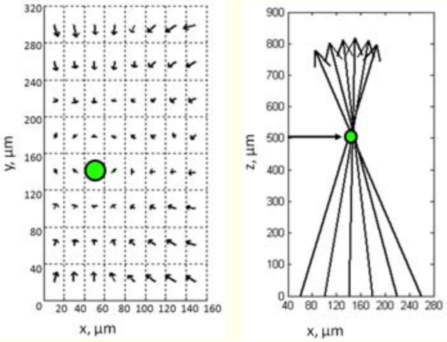

Figure 8: Measured vector fields from ASP array. For a single source, the vectors converge, allowing 3-D localization with high precision.

Future Work

To date, we have demonstrated a functional ASP that recovers useful angle information. We are presently addressing several remaining challenges:

- Size: Although the current ASP is pixel scale, its overall size is significantly larger than existing image sensor pixels.
- Robustness: The Talbot effect is sensitive to wavelength, so ASPs only perform optimally near a particular wavelength.
- Quantum Efficiency: The metal gratings required for angle determination dramatically reduce overall sensitivity to light.

Benefits and Opportunities

Cost and compatibility: ASPs can be manufactured in standard CMOS. This implies that:

- <u>Replacing existing CMOS imagers</u> with ASP arrays carries no real added cost.
- <u>Low cost sensors</u> can be manufactured (<$10)
- Little or no manufacturing development is needed - <u>Fabless model</u> applies

Enhanced photography: This technology enhances the pixels of CMOS image sensors, such as found in a digital camera or microscope. This implies:

- By capturing additional information about out-of-focus parts of a scene, <u>computational refocus</u> of those parts of the scene would be enabled.
- By capturing range information, this technology could enable <u>depth-mapping</u> of scenes, allowing for something similar to digital holography.

Lens-less imaging: By capturing incident angle, useful optical information becomes available without any lens at all:

- This would allow for simple sun or <u>object tracking</u> using nothing but the CMOS chip in question
- An array of ASPs can be used to characterize the <u>3-D structure of microscopic objects</u> (e.g. biomedical samples), without additional optical components. We see applications in:
  - Field deployable, low cost assays
  - Massively parallel assays at reasonable cost (for drug discovery, for example)

IP & Licensing information: PCT/US09/51660

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