Computational Photography

Independent Study Presentation 2:

Generalized Optics for Computational Photography

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Overview of the Presentation

- **Introduction**
  - Animal Eyes
  - Generalised Optics
- **Light Field**
  - Understanding Light field
  - Light Field Parameterization
  - Optical Element Formulation
  - Digital Camera Formulation
- **Optical Coding Approaches**
  - Generalized Optics Coding Approaches
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  - Object Side Coding Examples with Non-Homogenous Optical Element
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  - Basic Concepts of Pupil Plane Coding
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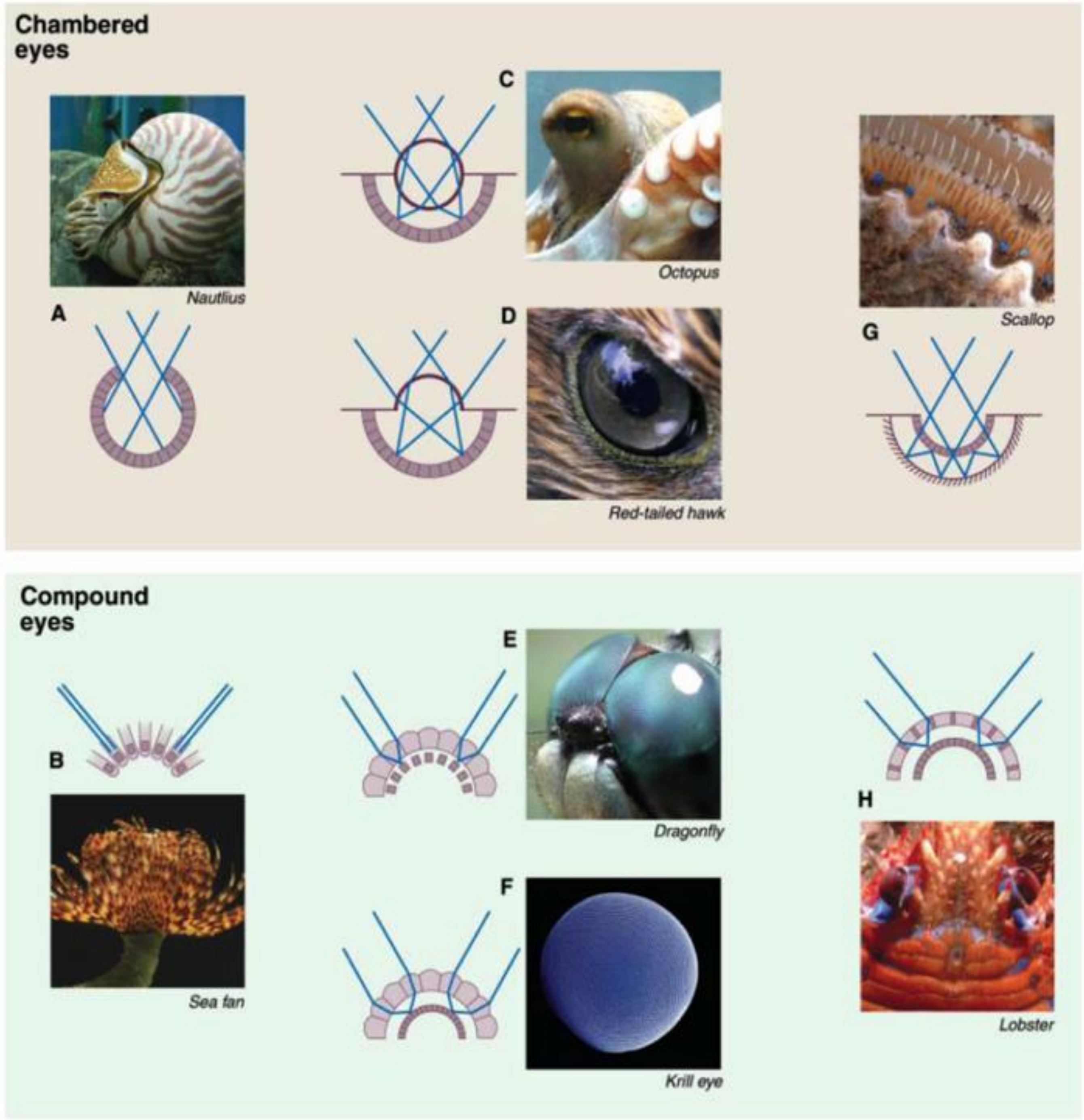
  - Wavefront Coding
- **Sensor Side Coding**
  - Basic Concepts of Sensor Side Coding
  - Fourier Slice Theorem
  - Coding In-front of the Sensor Plane
- **Conclusion**
  - Summary of Research using Generalized Optics
  - References

Introduction



Animal Eyes

Only 8 types of eyes in whole nature!!!

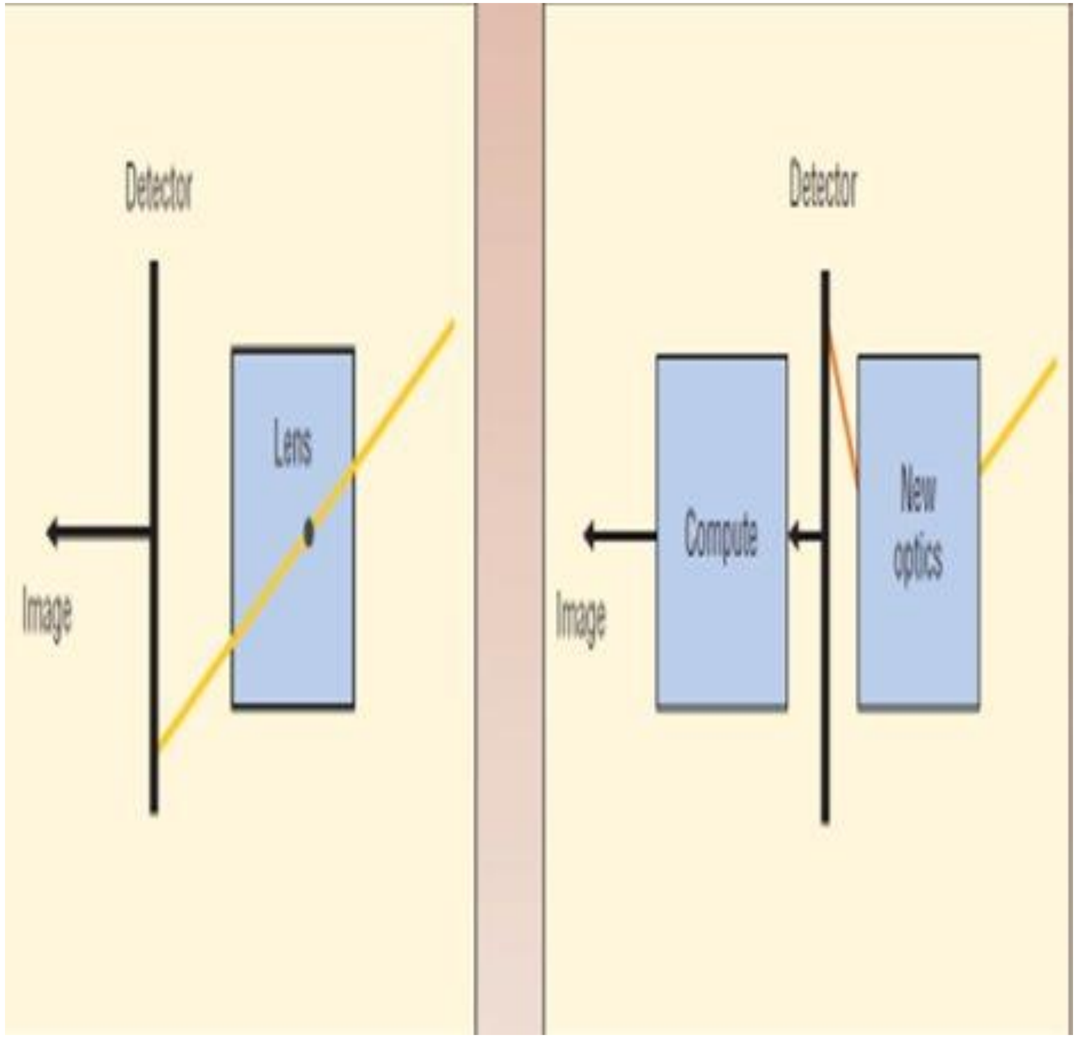
In 33 Animal Phyla-

- 1/3rd have no organs to detect eyes
- 1/3rd have light sensitive organs
- Only1/3rd have EYES!!!

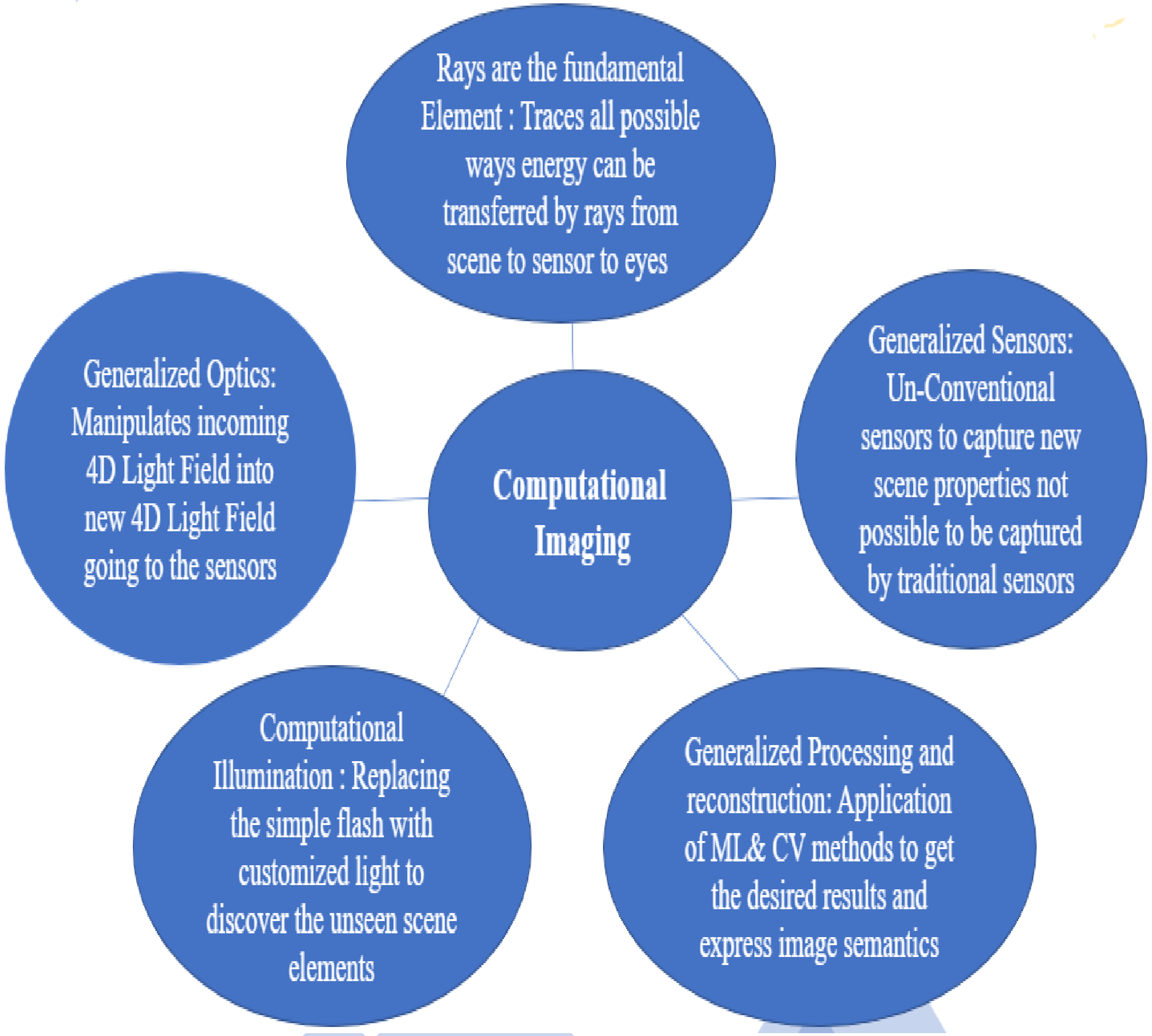
3 categories of eyes:

- Light detecting spots
- Chambered eyes
- Compound eyes

Generalized Optics



Digital Photography **Computational Photography**



Light Field

Understanding Light Field

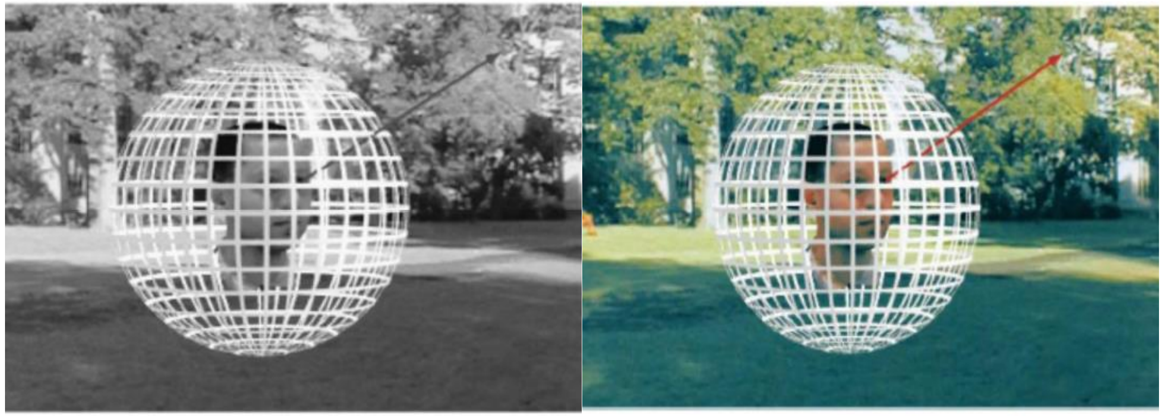
Complete Light Field is represented by:

$$L = P\,(x,\ y,\ z,\ \theta,\ \varphi,\ t,\ \lambda)$$

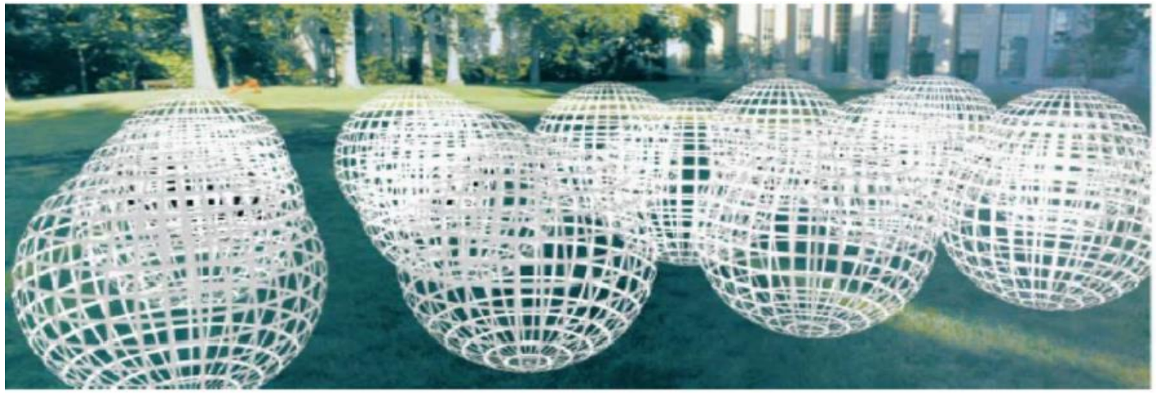
- a position in 3D space (3D)
- in a certain direction (2D)
- at a particular point in time (1D)
- in a particular wavelength (1D)

Space with obstacles Light Field : 5D
Space without obstacle Light Field: 4D

$$L = P\,(x,\ y,\ \cancel{z,}\ \theta,\ \varphi,\ \cancel{t,\ \lambda})$$

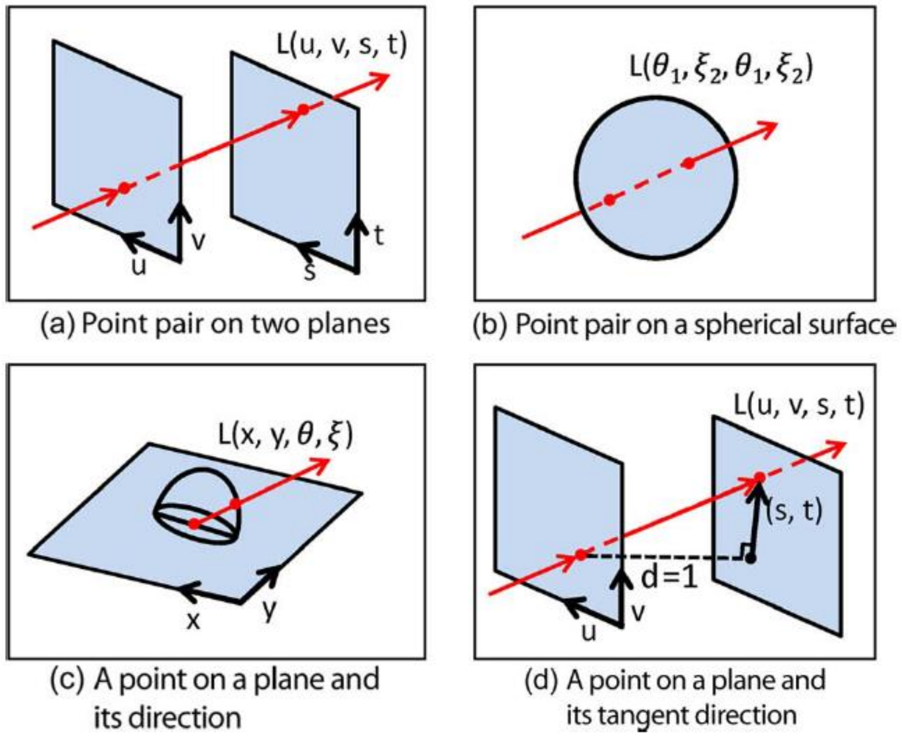


$P\ (\theta,\ \varphi)$ $P\ (\theta,\ \varphi,\ \lambda)$

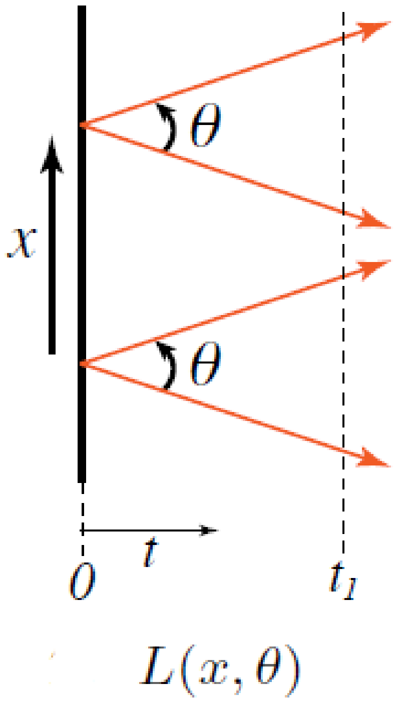


$P\ (\theta,\ \varphi,\ \lambda,\ t,\ x,\ y,\ z)$

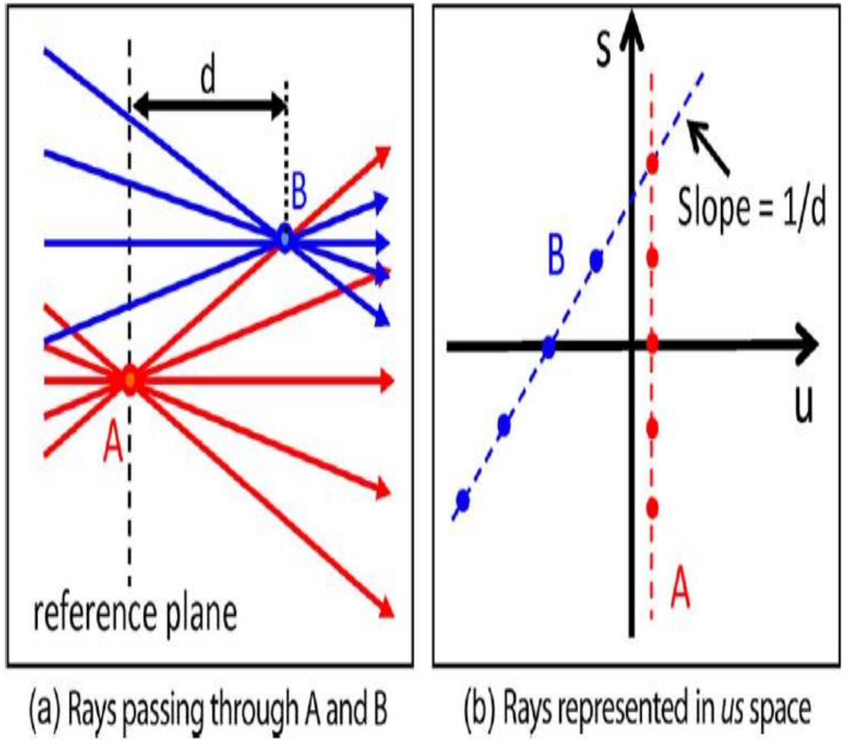
Light Field Parameterization



4 ways of Light Field Parameterization

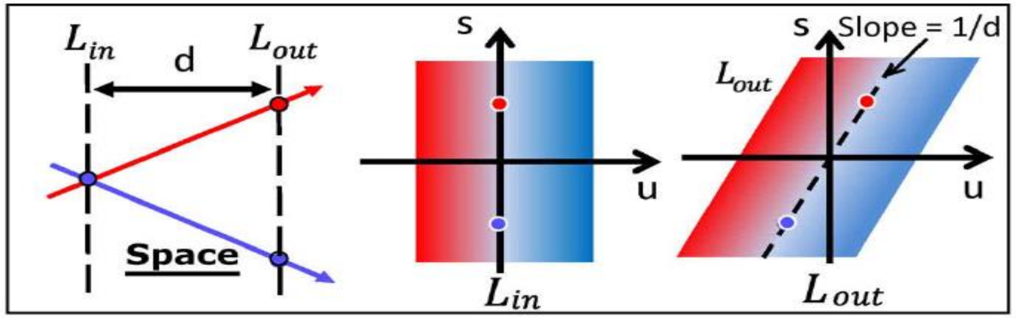


Simplification in 2D

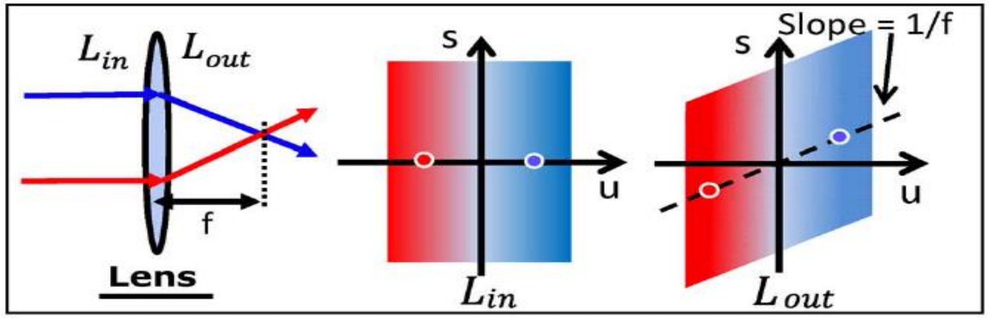


Ray Representation in u-s space

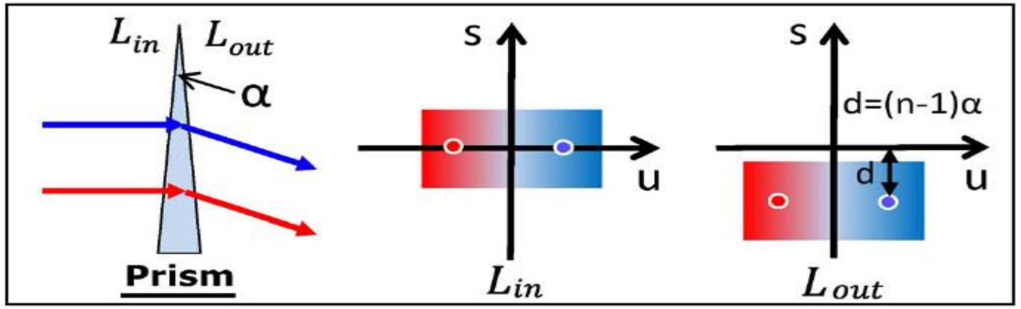
Optical Element Formulation



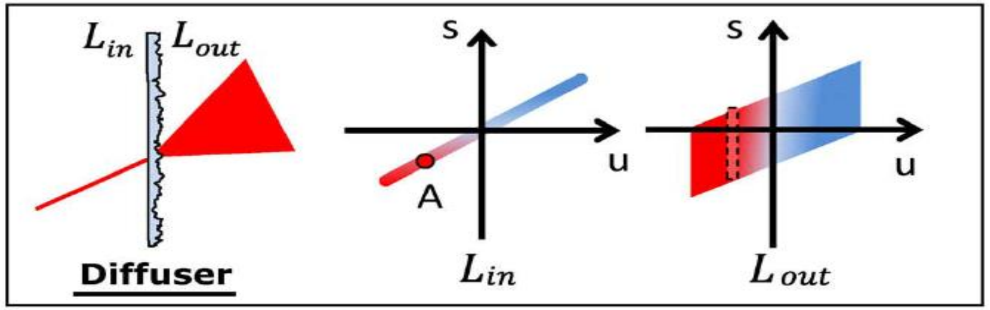
(a) Space propagation shears a light field in u dimension



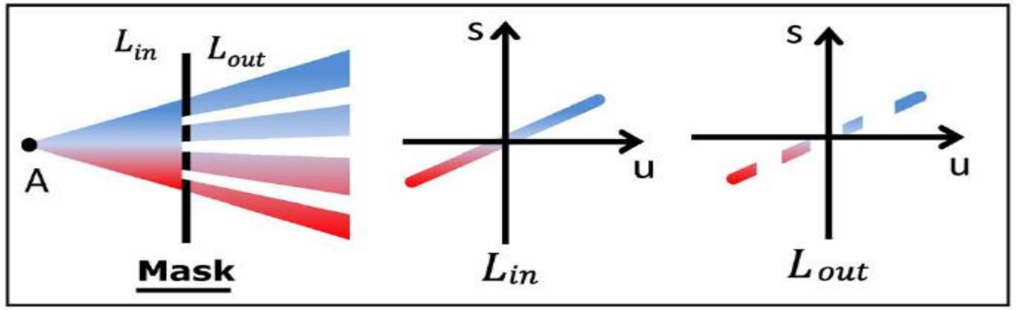
(b) A single lens shears a light field in s dimension



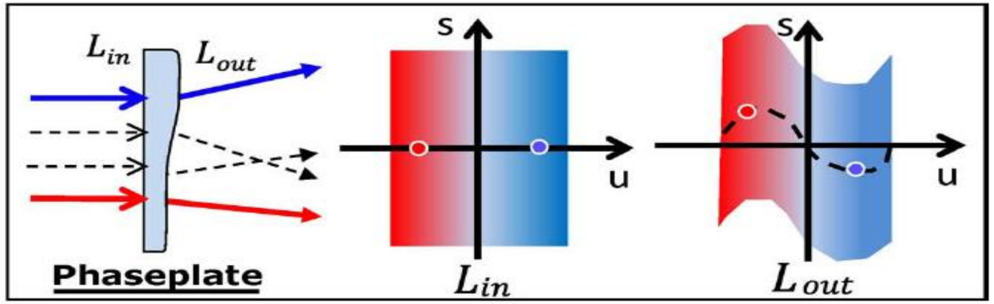
(c) A prism shifts a light field in s dimension



(d) An optical diffuser blurs a light field in s dimension

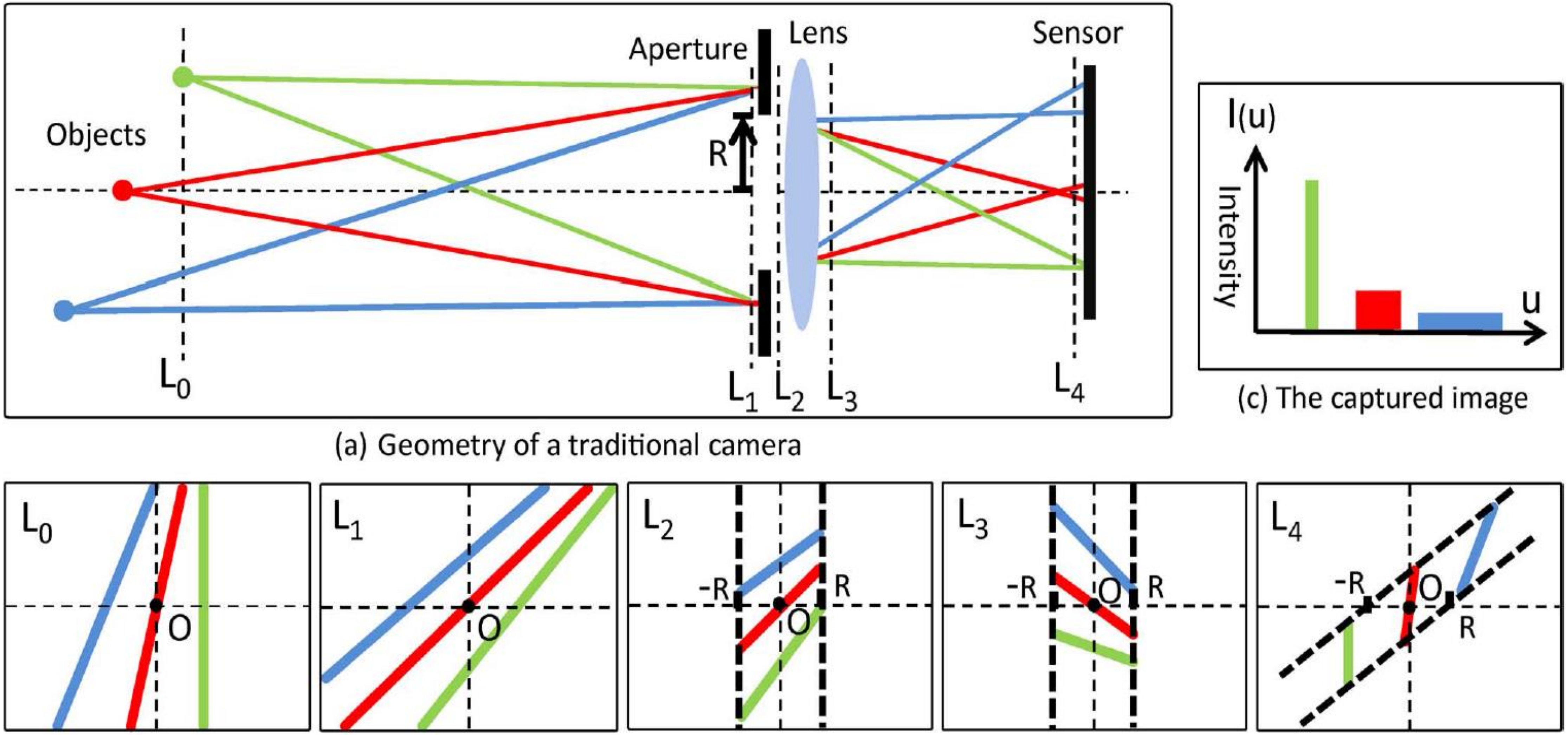


(e) A photomask performs a dot-product in u dimension



(f) A phase plate distorts a light field in s dimension

Digital Camera Formulation



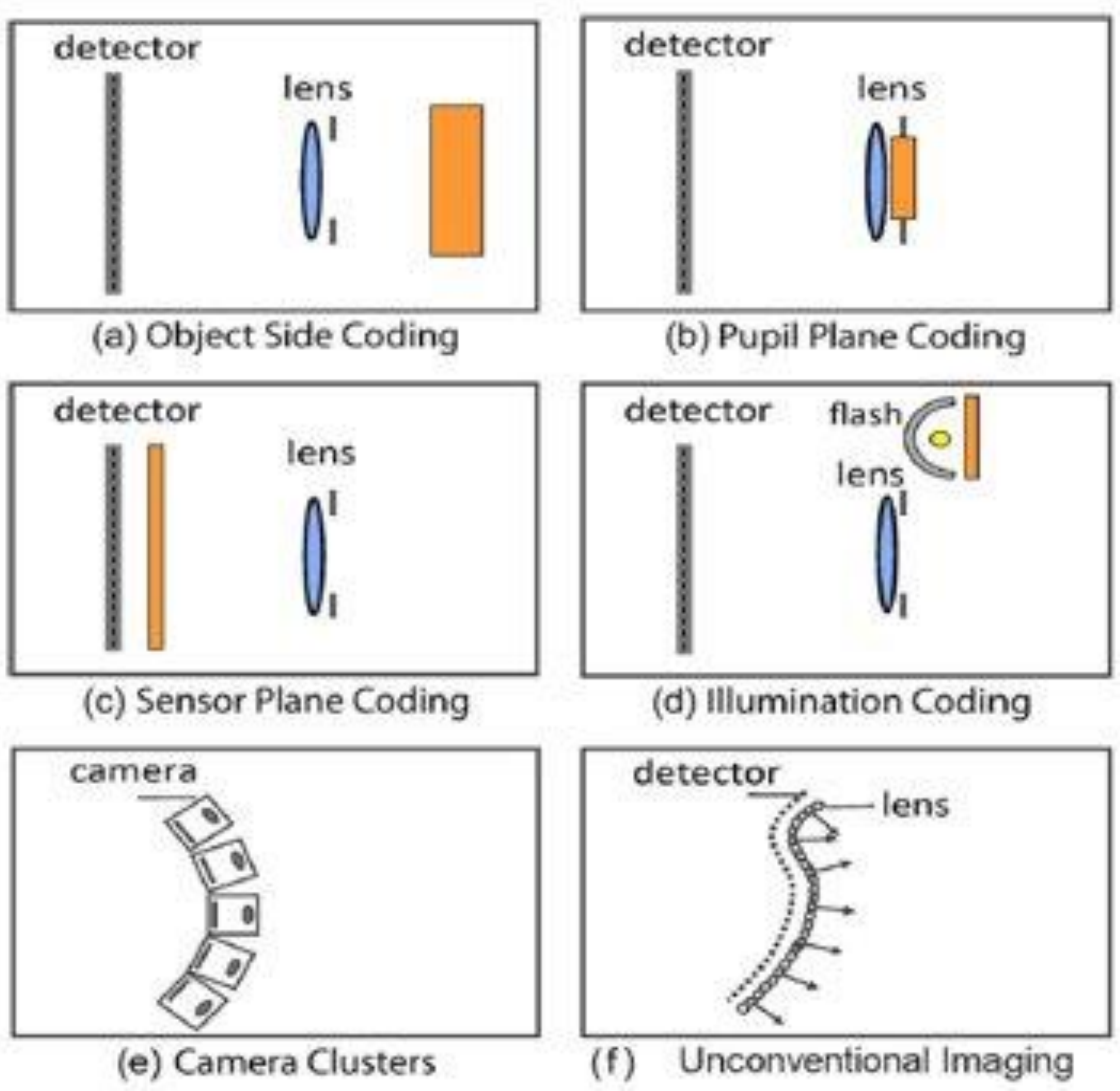
(a) Geometry of a traditional camera

(c) The captured image

(b) Five intermediate light fields between the scene and the sensor

Optical Coding Approaches

Optical Coding Approaches



Object side coding: An optical element is attached externally to the conventional Lens.

Pupil plane coding: An optical element is placed at, or close to, the aperture of the lens.

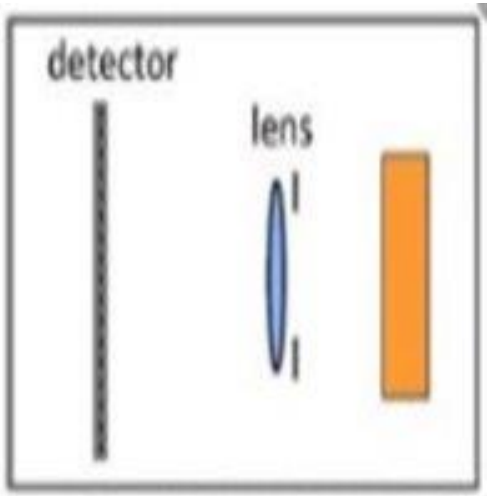
Sensor side coding: An optical element is placed behind the lens.

Illumination Coding: Imaging systems that program the illumination.

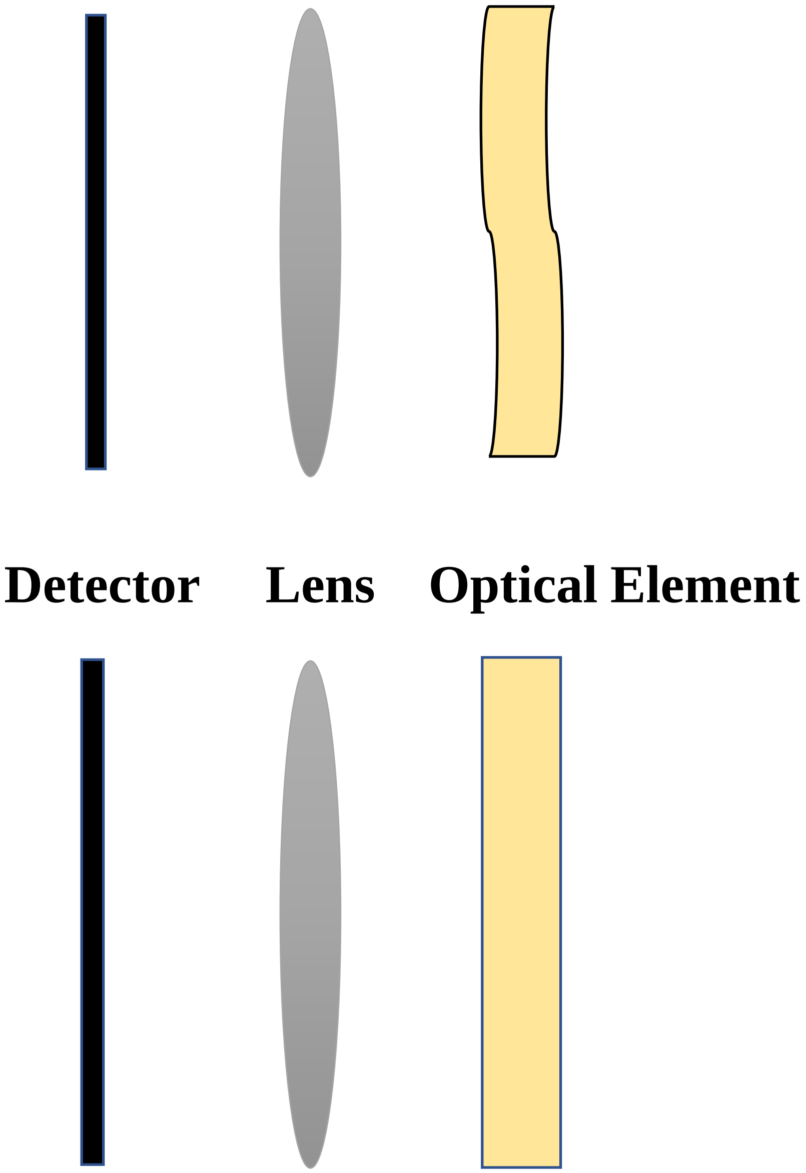
Camera Clusters: Imaging systems that are made up of a cluster or array of traditional camera modules.

Unconventional Imaging: Imaging systems using unconventional camera architectures or nonoptical devices.

Object Side Coding



Basic Concepts of Object Side Coding



When Optical Element is Non-Homogenous

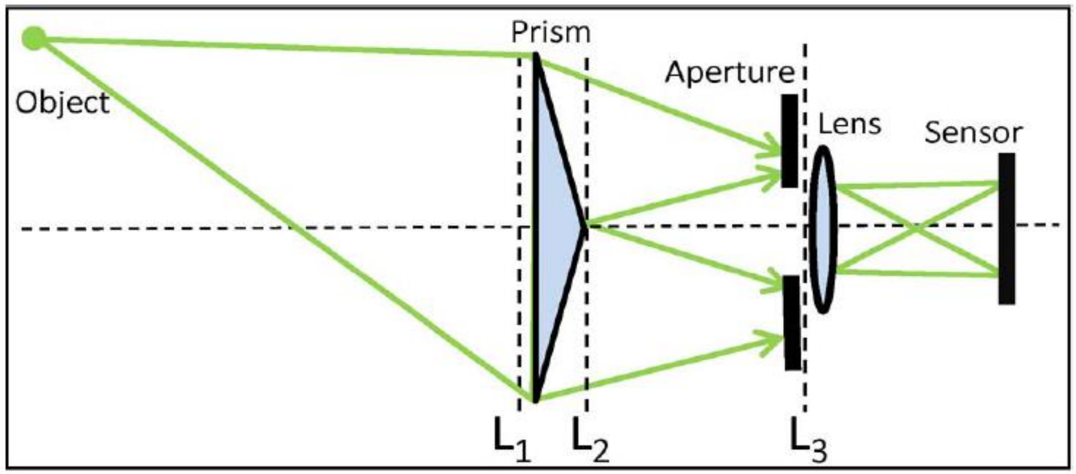
- The cones of light from the same point of object to the optical element will fall on different points on the optical element which are sheared to different locations on the lens.Hence, the modifications become spatially variant with viewing angle in a single shot.

When Optical Element is Homogenous

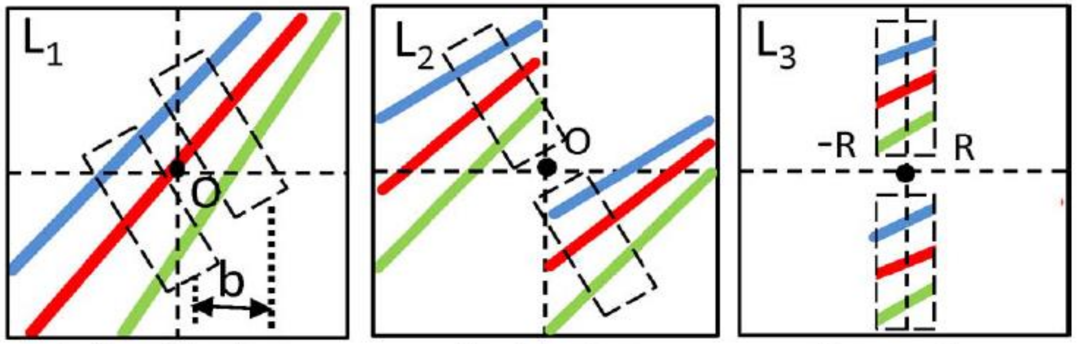
- The Modifications to the Incident Lightfield can be done temporally even though it provides spatially uniform manipulations to all the Lighfields

Object Side Coding Examples with Non-Homogenous Optical Element

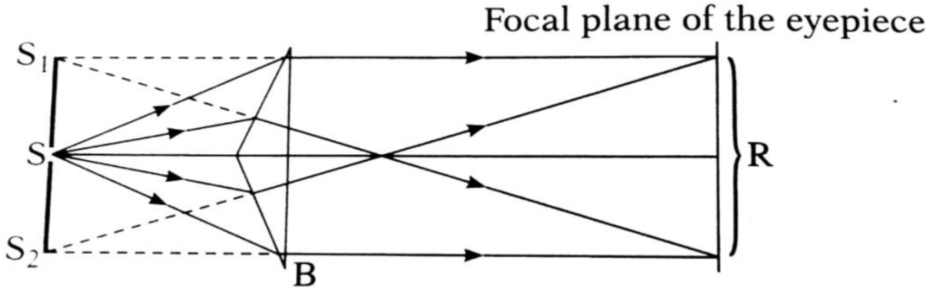
Depth Estimation



(a) Geometry of a bi-prism camera



(b) Light fields at three planes



S : Source (a slit illuminated by monochromatic light),
B : Biprism, S_1, S_2 : Virtual sources,
R : Region of interference

Bi –Prism

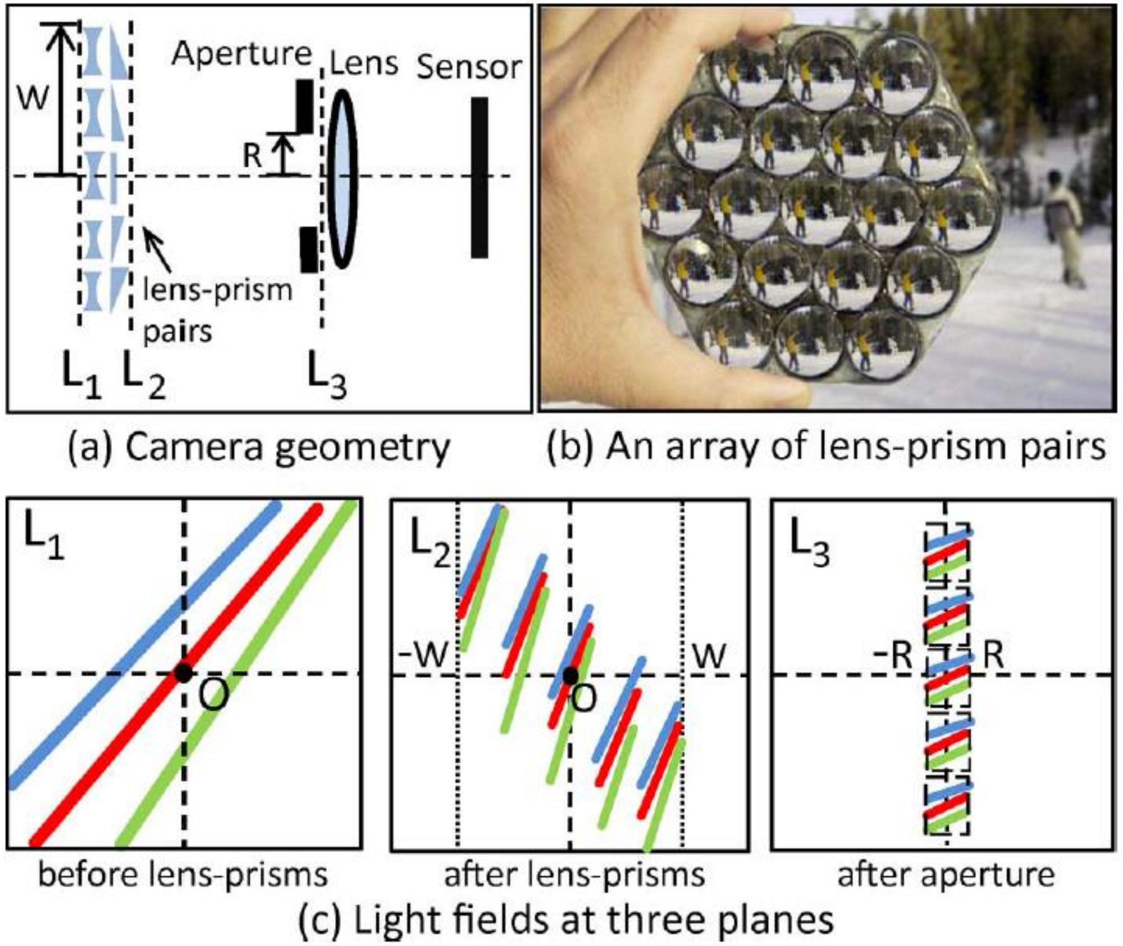
Baseline = 2*tan(α)*d

α--> Prism Angle

D--> distance b/w by-prism and lens

Object Side Coding Examples with Non-Homogenous Optical Element

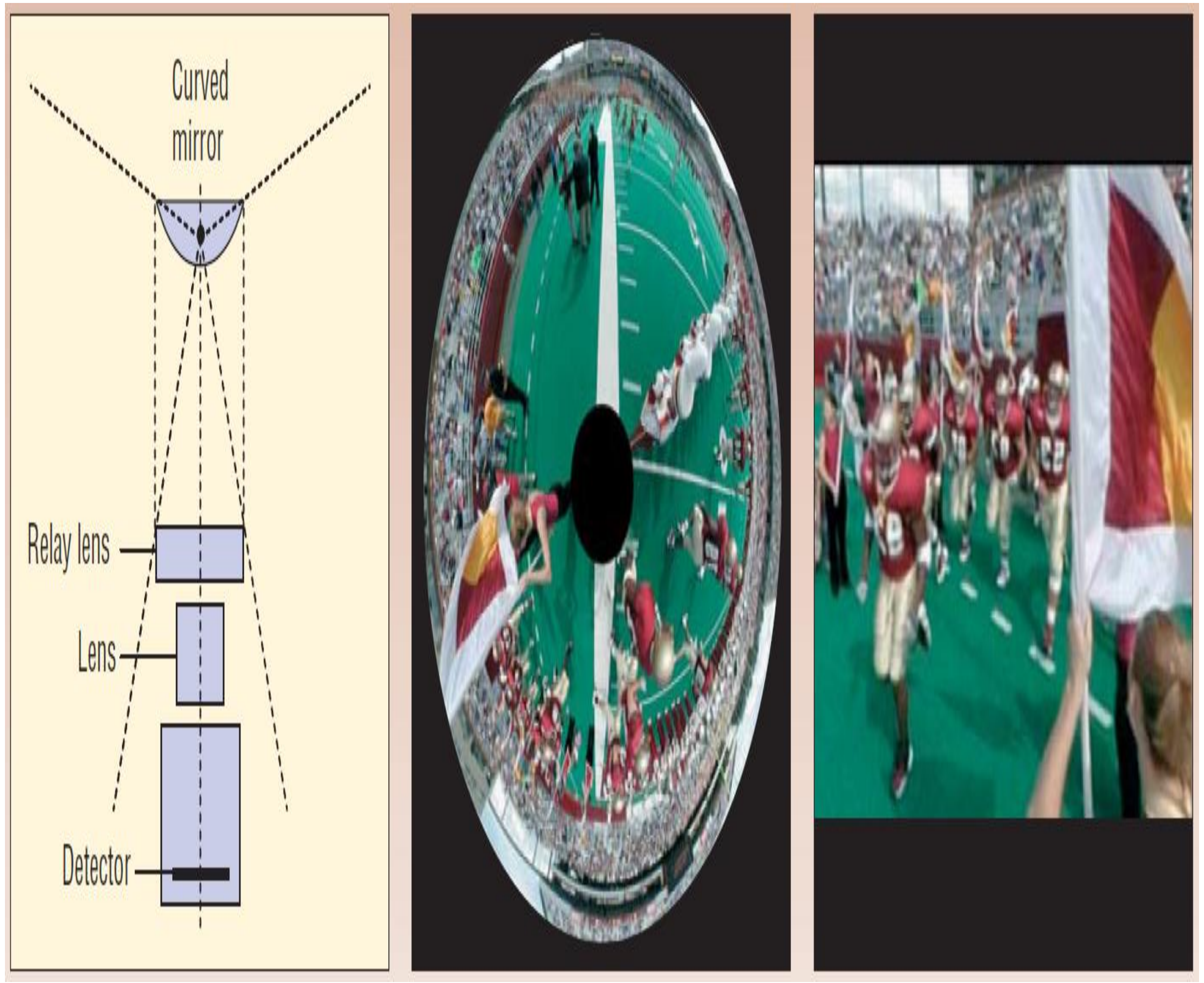
4D-Light Field Acquisition



- An array of by-prism is kept in-front of the Lens, with each prism having different deviation angle
- A Concave Lens is kept in-front of prism array to enhance FOV
- Multiple copies of the scene are obtained as if viewed from diferent angle.
- Hence, Light field can be aquired from a single image
- However, spatial resolution is compromised for the angular resolution

Object Side Coding Examples with Non-Homogenous Optical Element

Extending FOV



It’s a Catadioptric camera made by combining a lens and a mirror

It is designed to ensure that camera captures all the principle rays of the scene pass through the center of projection

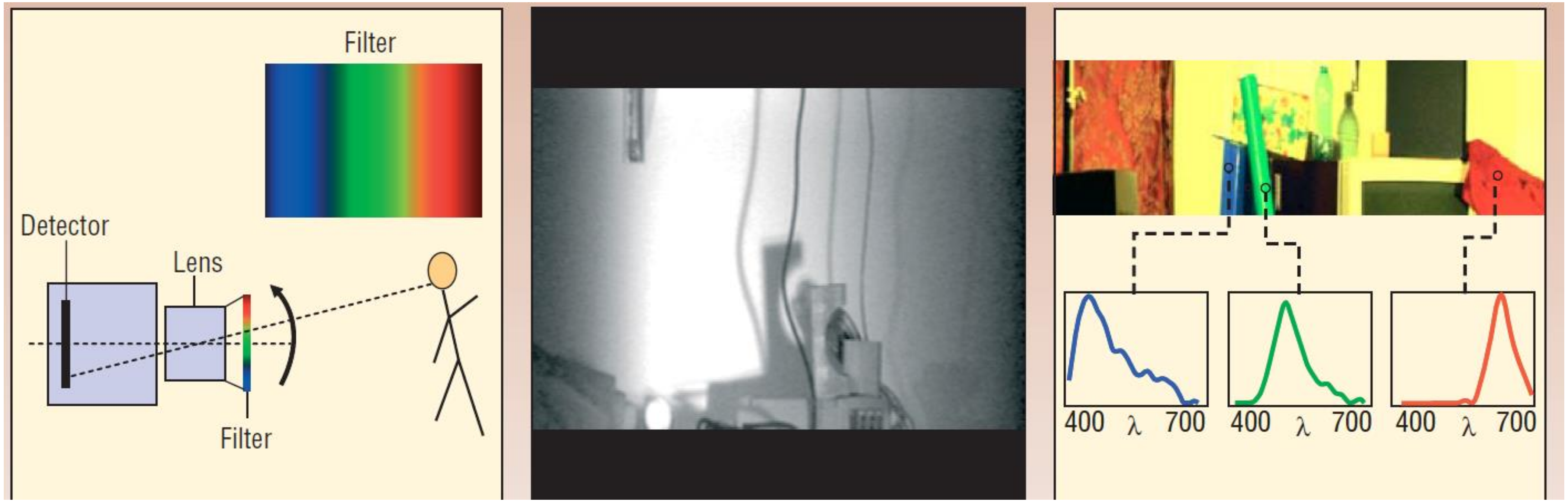
FOV in horizontal plane: 360 degree. FOV in vertical plane: 220 degree

The compressed image can be easily decoded to perspective image by a dedicated computational module at video rate

Method doesn't require static scene and only single camera & single shot is required

Object Side Coding Examples with Non-Homogenous Optical Element

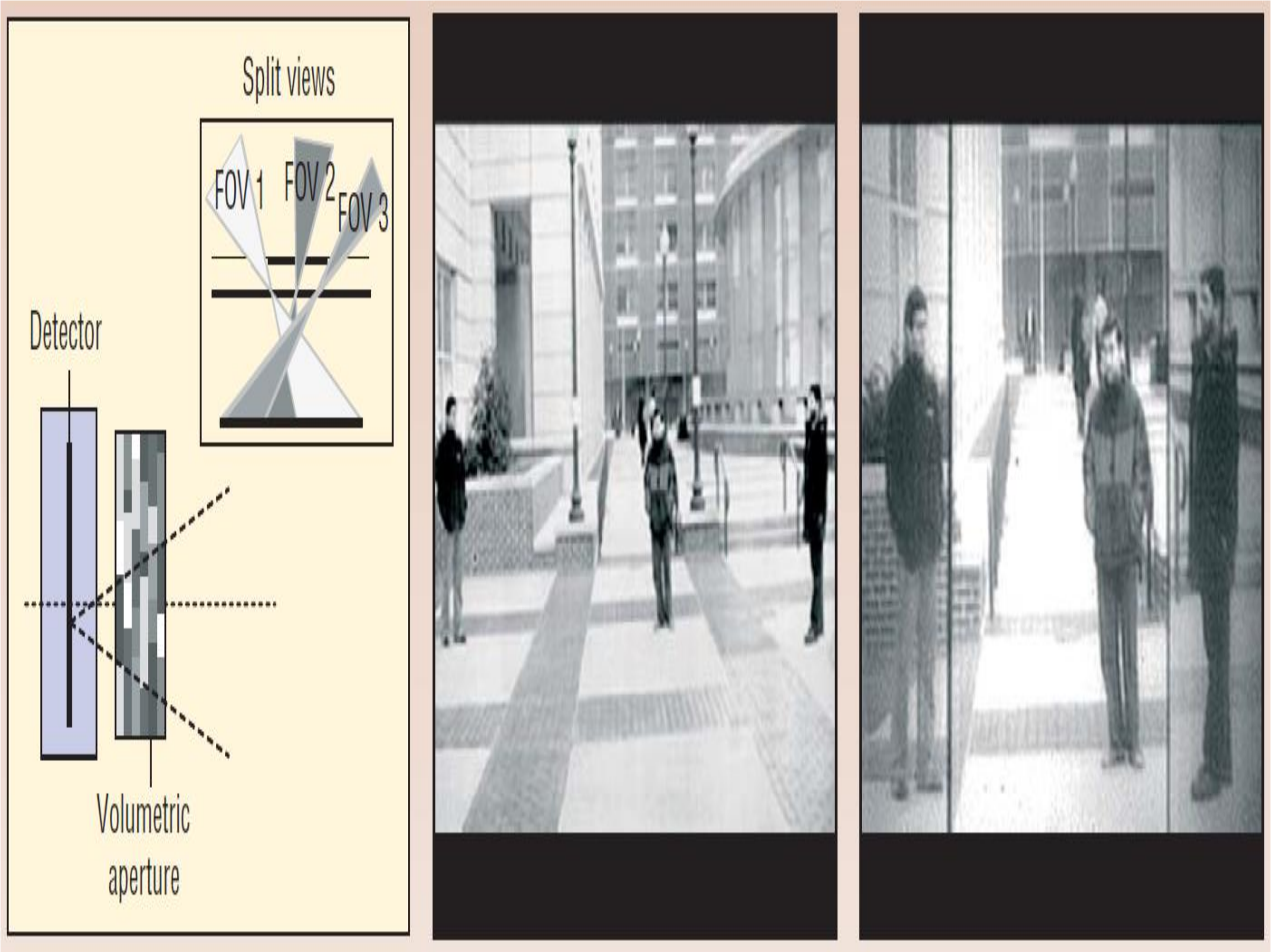
Multi-Spectral Imaging



Attaching a Linear Interference Filter having spatially varying property of passing different wavelength of visible spectrum,when attached to a black and white video camera it can capture multiple wavelength information of the scene which can be displayed together after interpolation using software.

Object Side Coding Examples with Non-Homogenous Optical Element

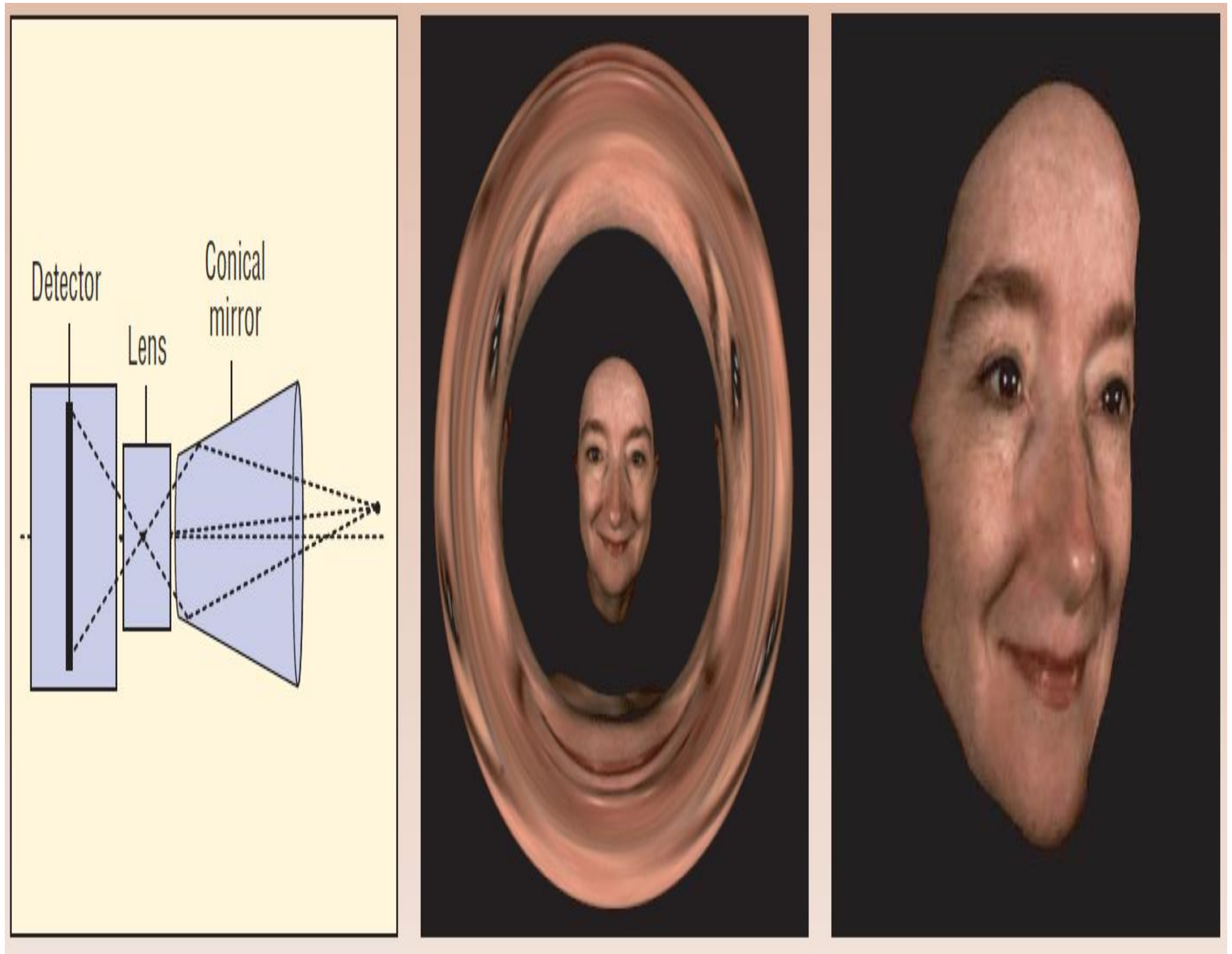
Split FOV (Lens-Less Imaging)



- It is designed by placing 3D(Volumetric Aperture) in front of the detector instead of Lens
- Proper arrangement of regions of full transmittance and zero transmittance across the volume can lead disconnected FOV to be mapped on adjacent sensor area
- The aperture is implemented as a stack of controllable 2D apertures. Each aperture is a liquid crystal (LC) sheet.
- One application is to image the desired FOV in higher resolution than wasting pixels on non-interest scene areas
- Further research scope lies in making the transmittance programmable and controllable.

Object Side Coding Examples with Homogenous Optical Element

Multi-View Radial Camera for 3D Imaging



A hollow cone, mirrored inside, is placed in-front of the traditional camera with the axes aligned.

Each scene point is imaged 3 times, once directy and 2 times after getting reflected from 2 point on the conical mirror.

Hence, 3 viewpoints are obtained. One is at the center of the sensor and the other 2 virtual viewpoints are equal and opposite wrt Optical axis on the sensor

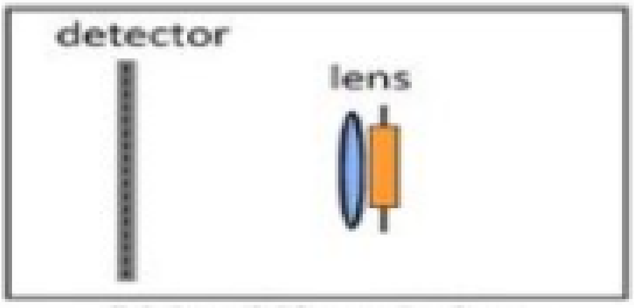
A Stereo Matching algo can find coreespondence between the 3 views and can give the depth information.

Object Side Coding Examples with Homogenous Optical Element

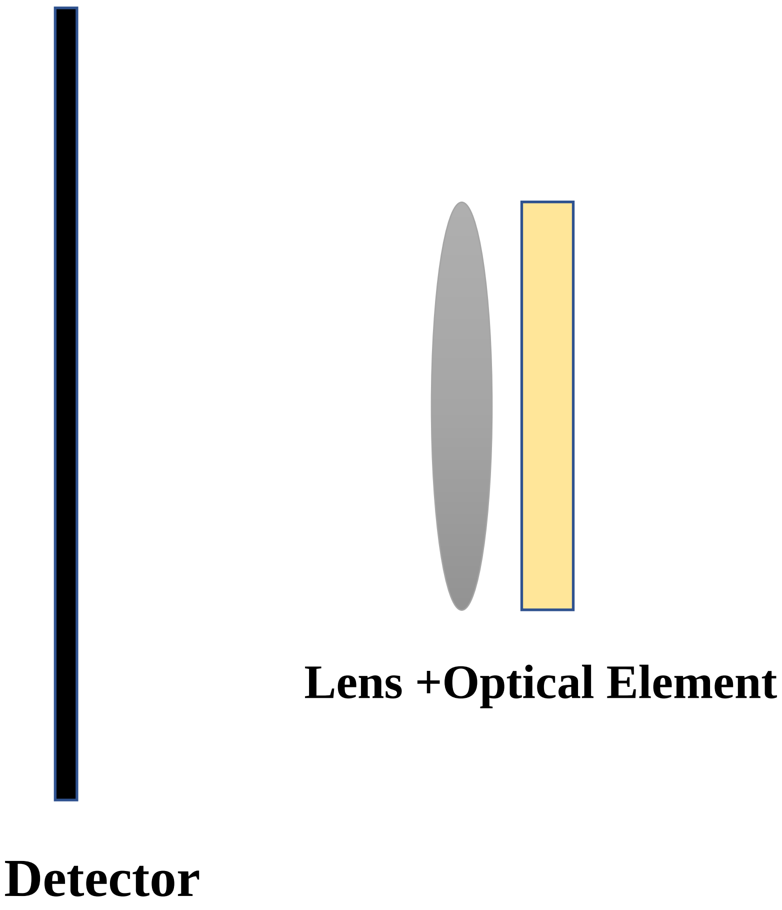
Other Applications

- Capturing image with different polarization direction in order to remove specular reflection
- Coding external shutter for coded exposure to remove motion blurring
- Placing Optical Diffuser on the object side for depth estimation as it gives larger angle triangulation etc.

Pupil Plane Coding



Basic Concepts of Pupil Plane Coding



Unlike Object Side Coding,Light reaching the Pupil Plane of the Lens is spatially invariant

Coding Done on the Pupil Plane has the aim of modifying the Point Spread Function of the Lens

The Fresnel equation describes the relation between the Pupil Plane Coding and Resulting PSF:

$$f(x) = \left|\mathcal{F}\left(W(x) \cdot Q_d(x)\right)\right|^2$$

$f(x)$	**PSF function**
$\mathcal{F}(\cdot)$	**Fourier Transform**
$W(x)$	**Aperture coding function**
$Q_d(x)$	**Quadratic Phase Term**

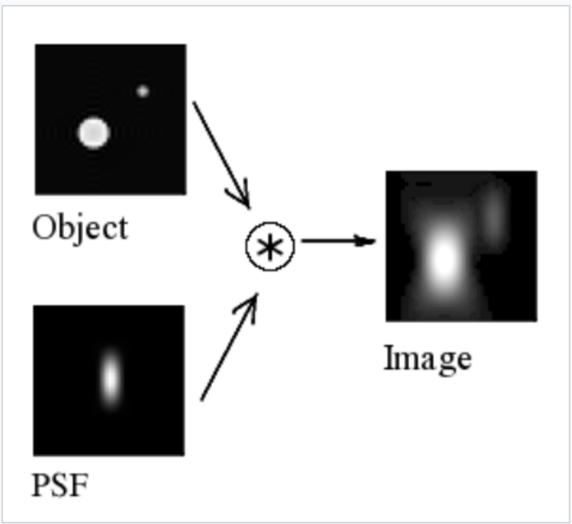
Point Spread Function

Point Spread Function:
It is a function that describes the response of a focussed imaging system to a point source at a given distance.

Finding Optimum Aperture Size at a given distance:

$$\delta = 2.44\lambda f/\delta$$

$$\delta_{opt} = \sqrt{2.44\,\lambda f}$$



$$i(x) = i_0(x) \otimes f(x).$$

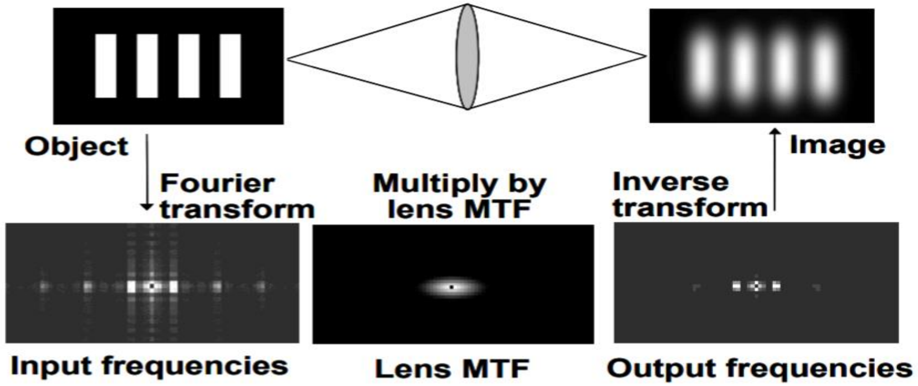
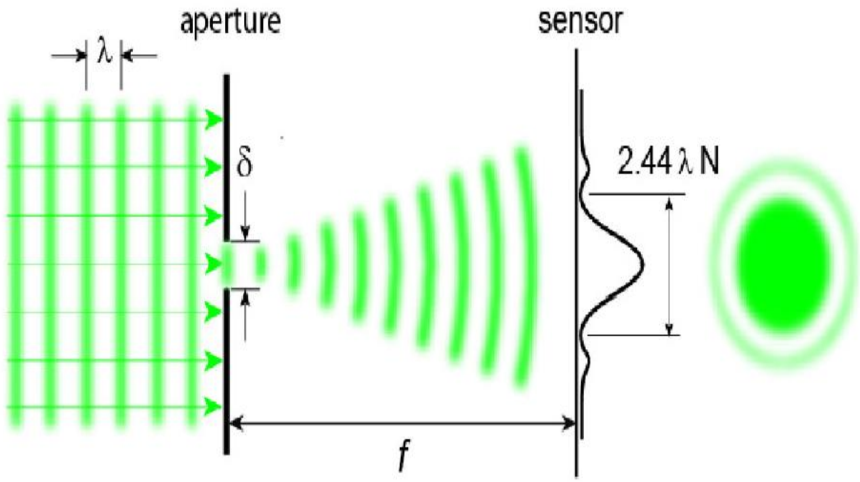
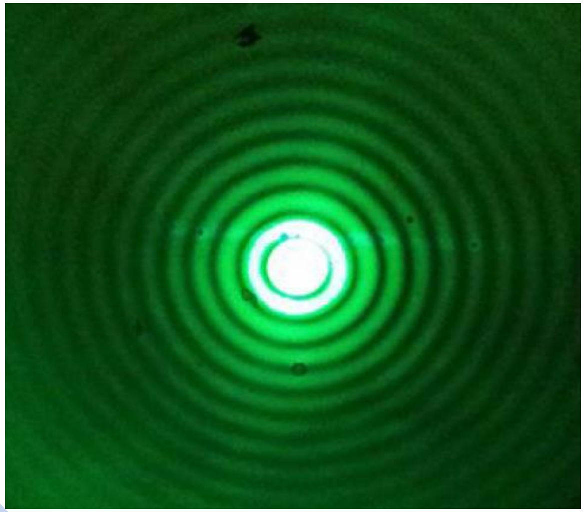


Figure 2.4 Frequency domain filtering in an optical system.





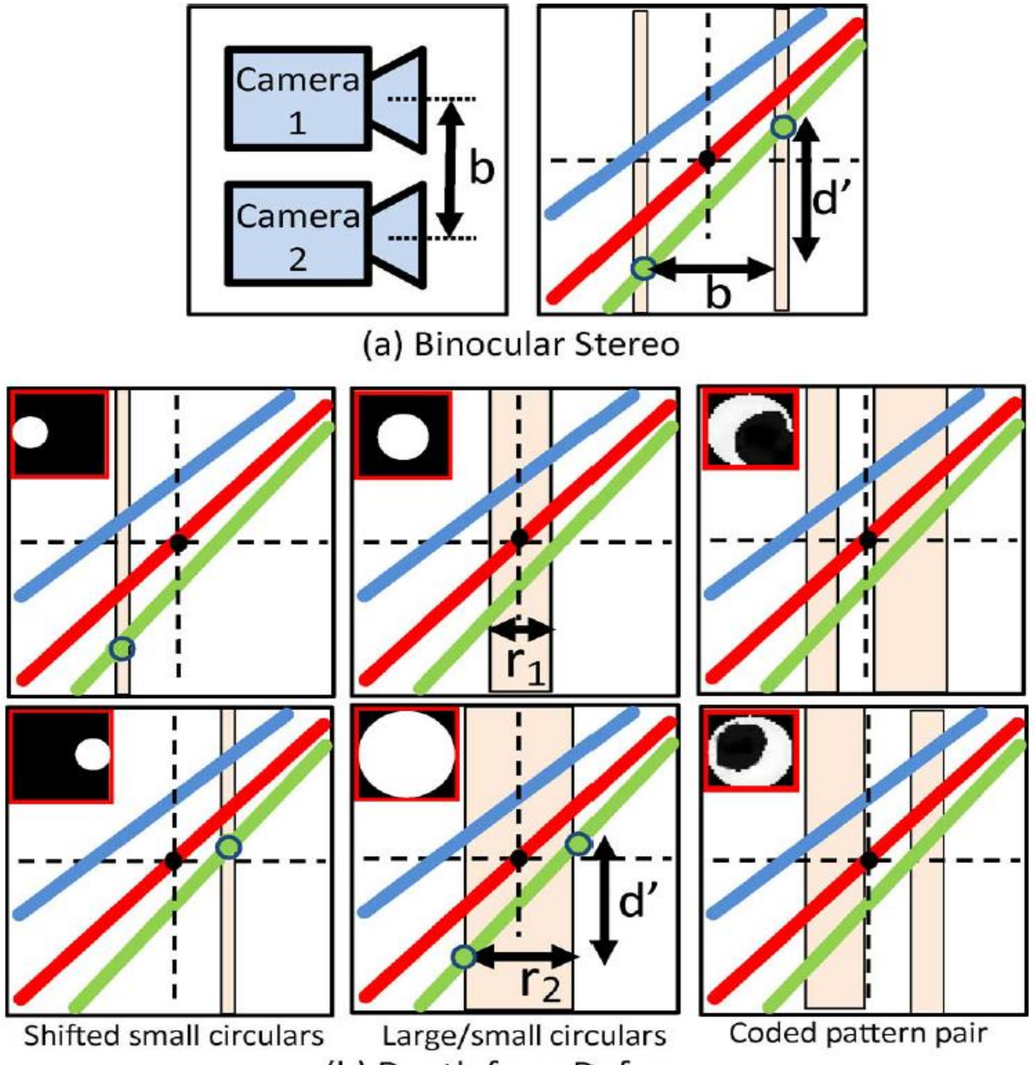
Small Aperture and the diffraction leading to Airy Disk and Diffraction Rings

Basic Concepts of Pupil Plane Coding

- Pupil Plane Coding
  - Coded Aperture
    - Involves Pupil Plane Coding with Intensity Modulators
    - Aperture Coding Function is Real
  - Wavefront Coding
    - Involves Pupil Plane Coding with Phase Modulators
    - Aperture Coding Function is Complex

Coded Aperture

Depth from Defocus



(a) Binocular Stereo

(b) Depth from Defocus

Here we compare Binocular Stereo with the Coded Aperture Technique for calculating the Scene Depth

In terms of Light Field Representation,Slope of a stripe is inverse of the depth. So both the techniques go for Slope Calculation

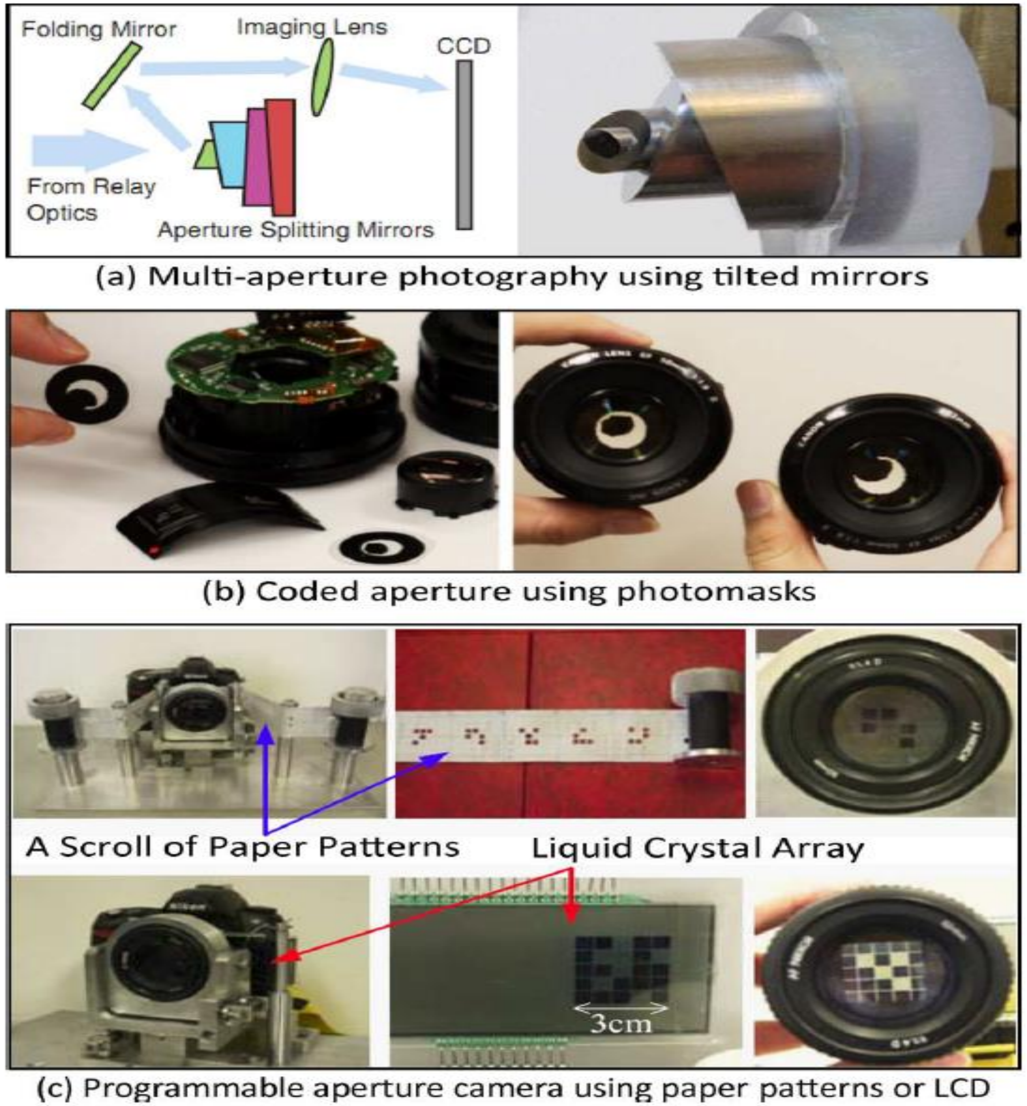
Binocular Stereo establishes the correspondences and calculate (focal length normalized disparity)/(baseline)

DFD using Coded Aperture calculate different integral across each stripe to calculate blur kernel size by DFD algo

Slope for DFD is (focal length normalized blur kernel radius)/(aperture diameter)

Coded Aperture

Other Applications



Defocus Deblurring

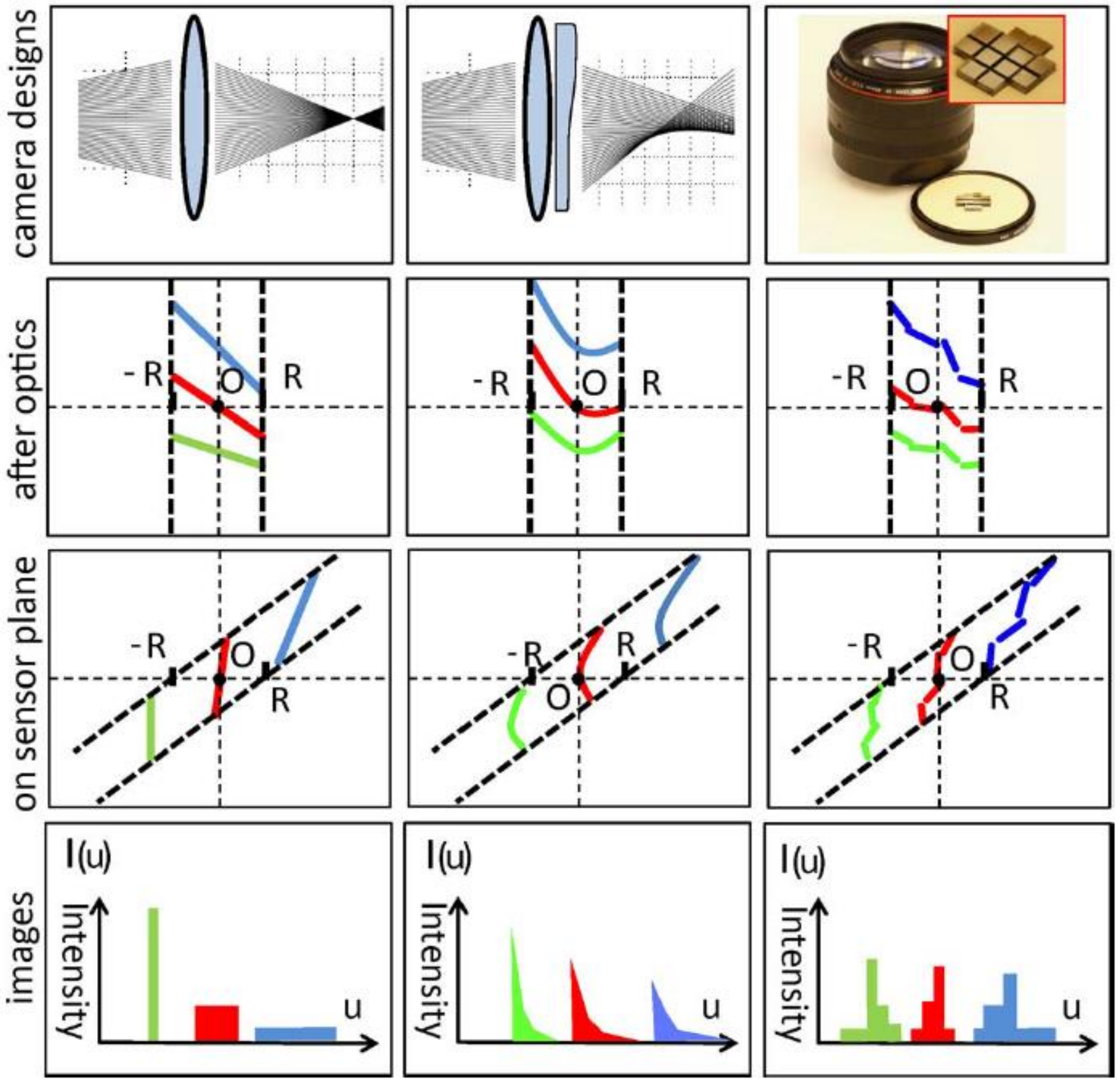
- If Point Spread Function is known,then deconvolving the captured image with PSF gives high quality sharp image.
- Coded Aperture can help in getting broadband MTF with limited and known zero crossing frequencies

Depth Using Coded Aperture for colors

- Color Filter Apertures so that 3 color channels are captured with different apertures
- Depth information can be obtained by processing each channel image seprately

Wavefront Coding

Extending Depth of Field



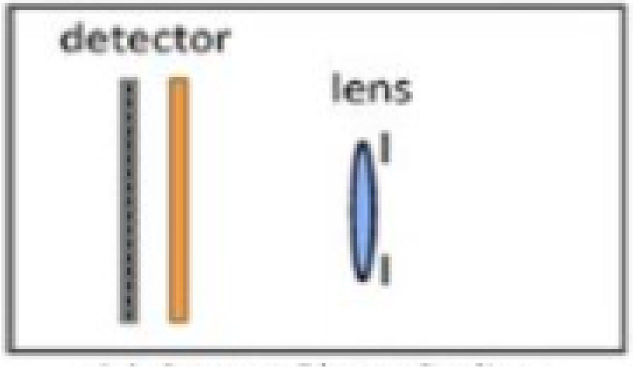
TraditionalCamera **Wavefront coding** **Lattice-focal Lens**

A cubic phase plate having Aperture Coding function a third order polynomial is used

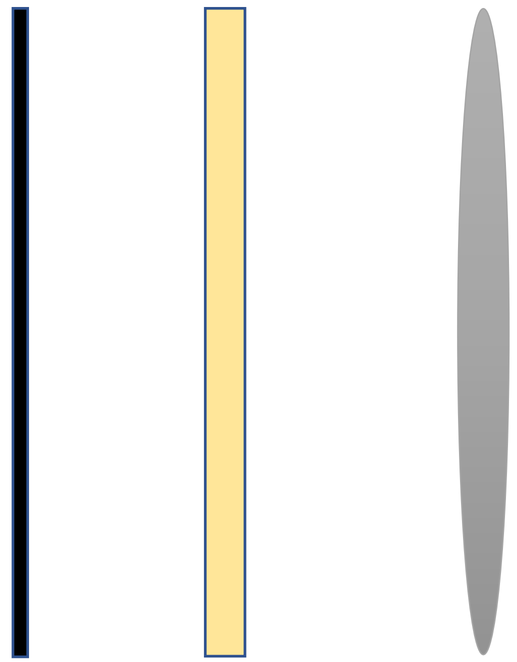
It results in a broadband MTF without zero-crossing frequencies and is depth invariant as cubic polynomial overpowers the quadratic term varying with depth

The Intensity of a ray falling on the sensor plane depends on its alignment with sensor plane.So the phase plate tilts the light field in a way that images are sharp irrespective of the depth

Sensor Side Coding



Basic Concepts of Sensor Side Coding



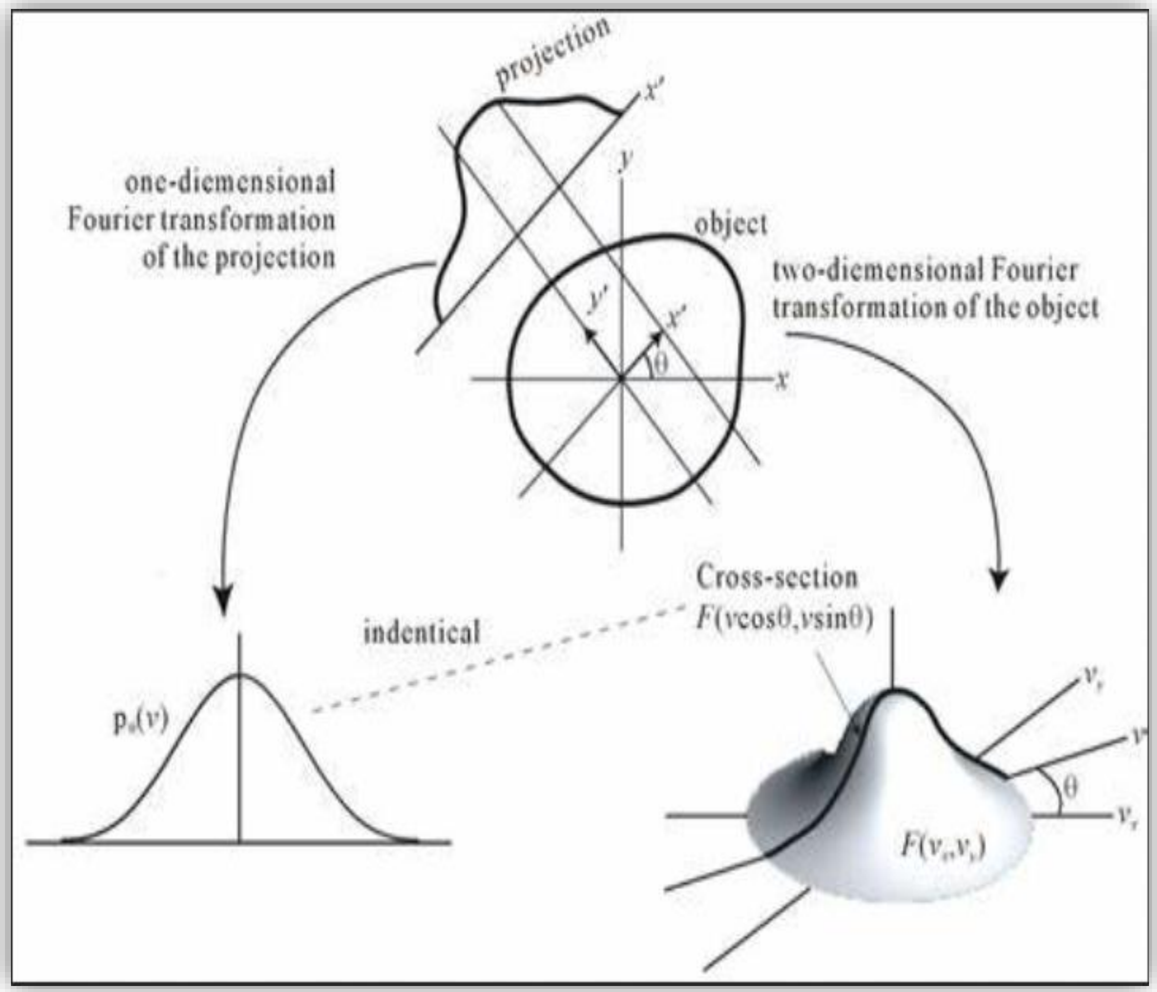
Detector **Optical Element** **Lens**

Optical Element kept on the sensor side of the Lens provides non-convetional optics

According to Gauss Law, Optical Devices after the lens are the dual of the optical devices infront of the lens.Hence, sensor side coding can provide same functionalities as object side coding

Advantage of Sensor Side Coding is that it provide compact solutions which are non-intrusive for scene

Fourier Slice Theorem



Fourier Slice Theorem Depiction

The Fourier Slice Theorem

- **Let**

$$P_\theta(\rho) = CTFT\{p_\theta(r)\}$$
$$F(u,v) = CSFT\{f(x,y)\}$$

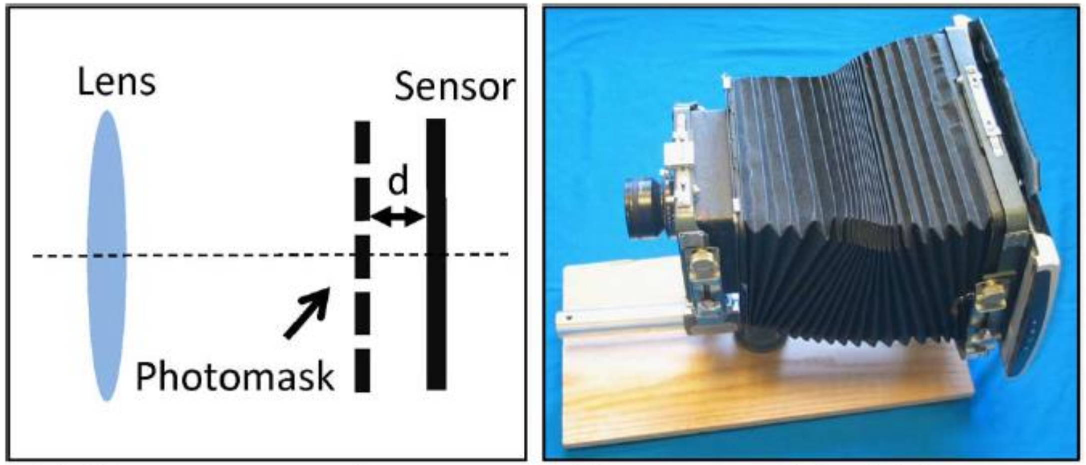
Then

$$P_\theta(\rho) = F(\rho\cos(\theta), \rho\sin(\theta))$$

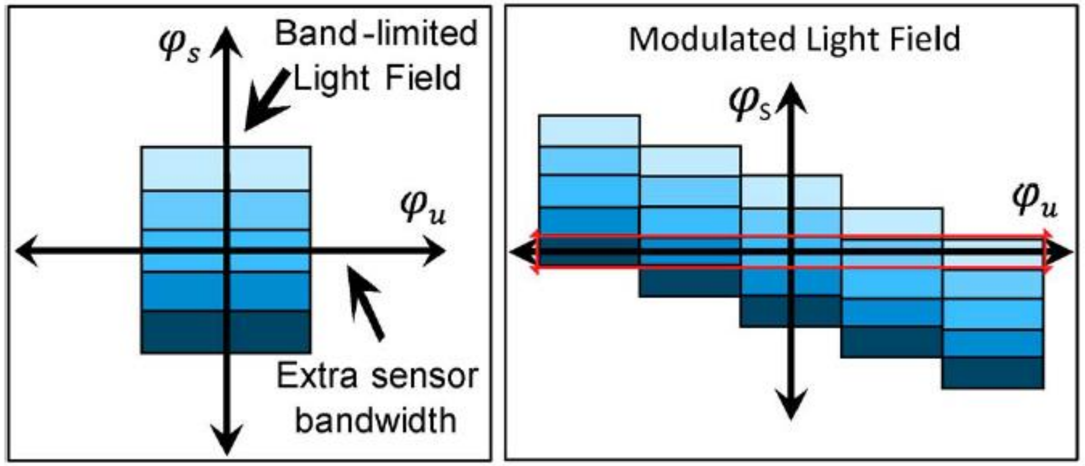
Fourier Slice Theorem Equations

Coding in-front of the Sensor Plane

Light Field Acquisition



(a) The geometry and a prototype of heterodyne light field camera



without photomask

with photomask

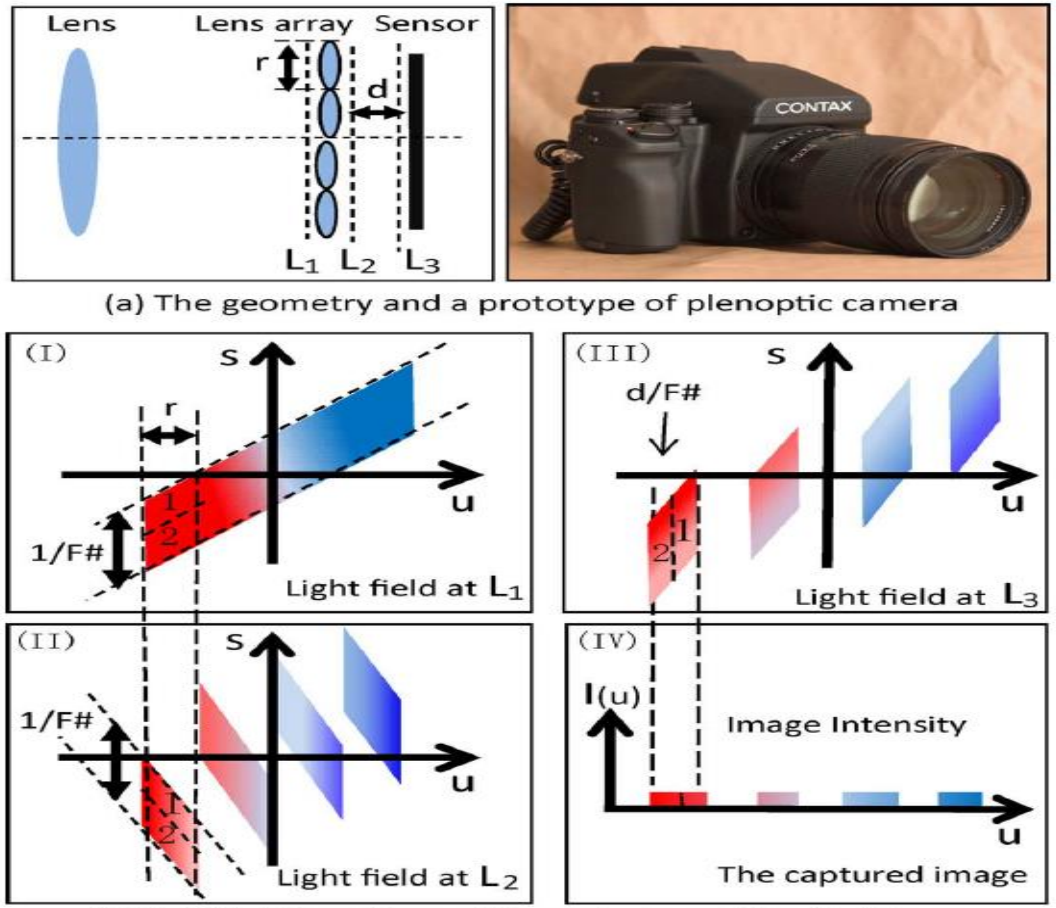
(b) Light field on sensor plane in the Fourier domain

$$I = \mathcal{P}[\mathcal{S}[L \cdot M]] = \mathcal{P}[\mathcal{S}[L] \cdot \mathcal{S}[M]] = \mathcal{P}[L_5 \cdot \mathcal{S}[M]]$$

M is the shifted cosine signal in spatial domain or shifted Dirac Delta function in Fourier Domain which on getting multiplied with L5 gives multiple copies of L5 each tilted with respect to each other in spatial domain.Each tilted copy projects different projection on the sensor which when combined yields 4D Light Field

Coding in-front of the Sensor Plane

Light Field Acquisition



(a) The geometry and a prototype of plenoptic camera

(b) Light field transform at three planes and the final image

The figure demonstrates how the lens array helps in mapping two field components of different angle on same location to be mapped separately which is not possible with traditional camera.

Conclusion

Summary of Research using Generalized Optics

	Devices	Object Side Coding	Pupil Plane Coding	Sensor Side Coding
Phase Modulators	Lens(es)	Lightfield: [52, 11]	Depth: [104]	Lightfield: [113,114,111,115,116,206]
	Prism(s) Plate(s)	Depth: [46,50,208,209] Color: [72]		
	Phaseplate		Depth: [98, 99] EDOF: [100,101,105,106,107,210]	
	Diffuser	Depth: [31] HDR: [77]	EDOF: [32,108]	
Intensity Modulators	Photomask	HDR: [33,70,215] Motion: [76]	Lightfield: [37,38] EDOF: [94,95] Depth: [34,80,81,82,83,84,89,90,217,218] Image: [34,35,36,85,86,87,88,211,212,213]	Lightfield: [35] HDR: [110,121,214]
	Color Filter	Color: [33]	Depth: [45]	Color: [43,116,117,119,120,121]
	Polarizer	Separation: [73,74,75,219,220]		
Others	Motion	EDOF: [132]	Depth: [221]	EDOF: [134] Image: [133,134,135] Motion: [76,112,136]
	Mirror(s)	Depth: [47,48,49,51,71,223,226] FOV: [53,54,55,56,57,58,59,60,64, 65,66,67,68,69,71,222,224,225]		HDR: [41,97,215] FOV: [41]

References

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- https://www.youtube.com/watch?v=Koq19e4xVgg&list=PLjRBT0-8H-NHkA7JxZ4b4o5WDgFcbghOd&index=5
- https://www.youtube.com/watch?v=Tkc_GOCjx7E
- www.computationalphotography.org

Thank You!!!