Coding and Modulation in Cameras

Ramesh Raskar
with Ashok Veeraraghavan, Amit Agrawal, Jack Tumblin, Ankit Mohan

Mitsubishi Electric Research Labs (MERL)
Cambridge, MA

Coding in Time

Overview

- Coded Exposure
  - Motion Deblurring

Coding in Space

- Coded Aperture
  - Digital Refocussing
    - Extended depth of field
  - Optical Heterodyning
    - Light Field Capture
    - 4D to 2D mapping


Motion Blurred Input Photo

Approximate rectified crop of photo

Image Deblurred by solving a linear system. No post-processing

Flutter Shutter Camera

Raskar, Agrawal, Tumblin [Siggraph2006]

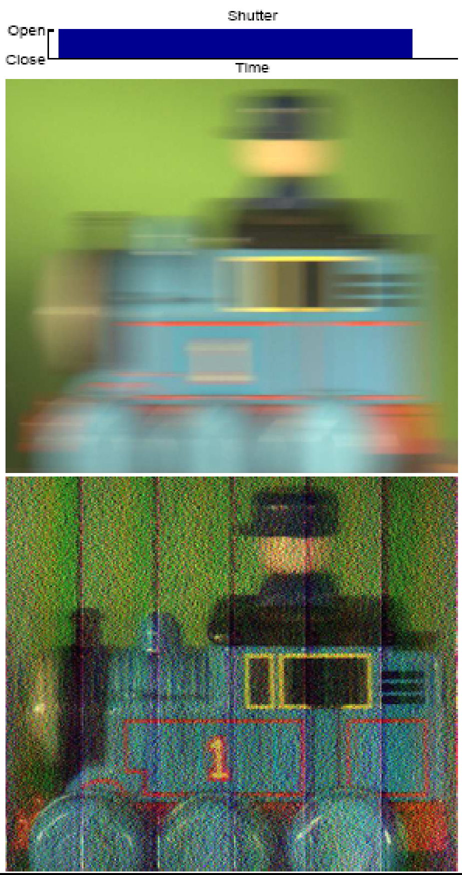
Ferroelectric LCD shutter in front of the lens is turned opaque or transparent in a rapid binary sequence

Coded Exposure Photography:
Assisting Motion Deblurring using Fluttered Shutter

Short Exposure

Image is dark and noisy

Traditional



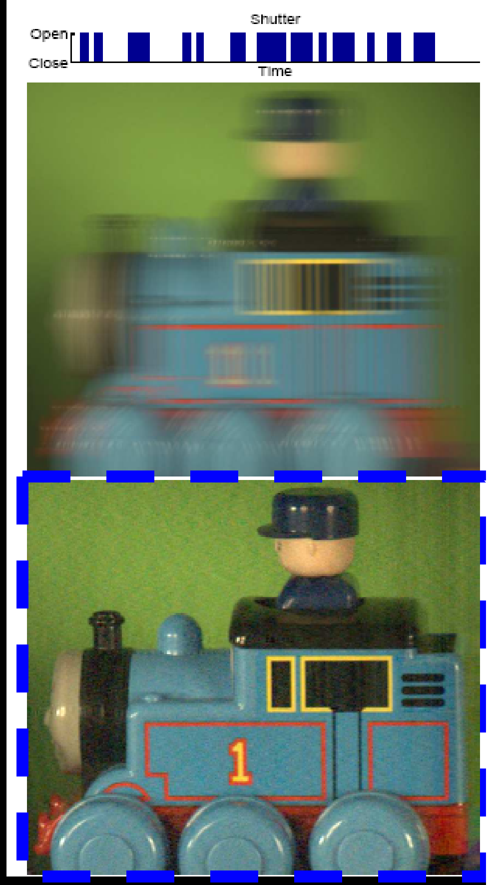
Result has Banding Artifacts and some spatial frequencies are lost

← Shutter →

← Captured Single Photo →

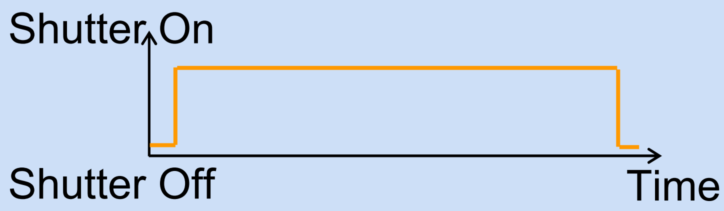
← Deblurred Result →

Coded



Decoded image is as good as image of a static scene

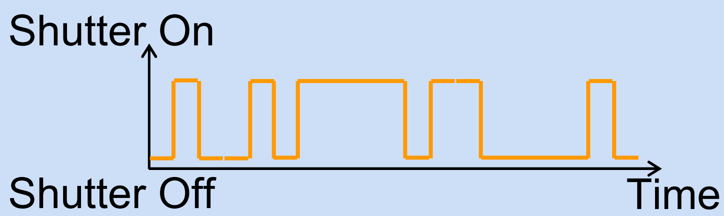
Exposure choices for capturing fast moving objects



Traditional Camera

Keep Shutter open for entire exposure duration

The moving object creates smear

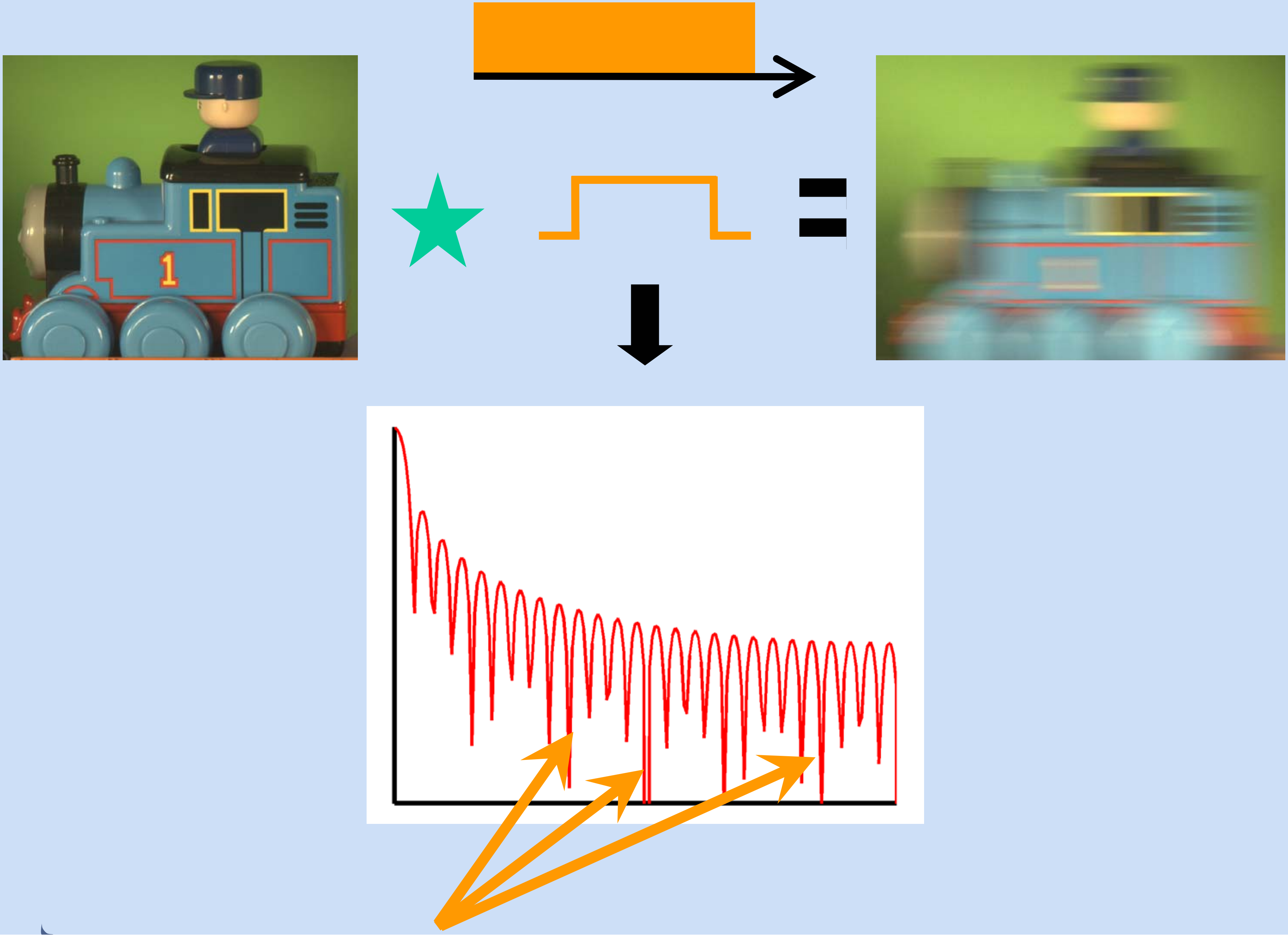


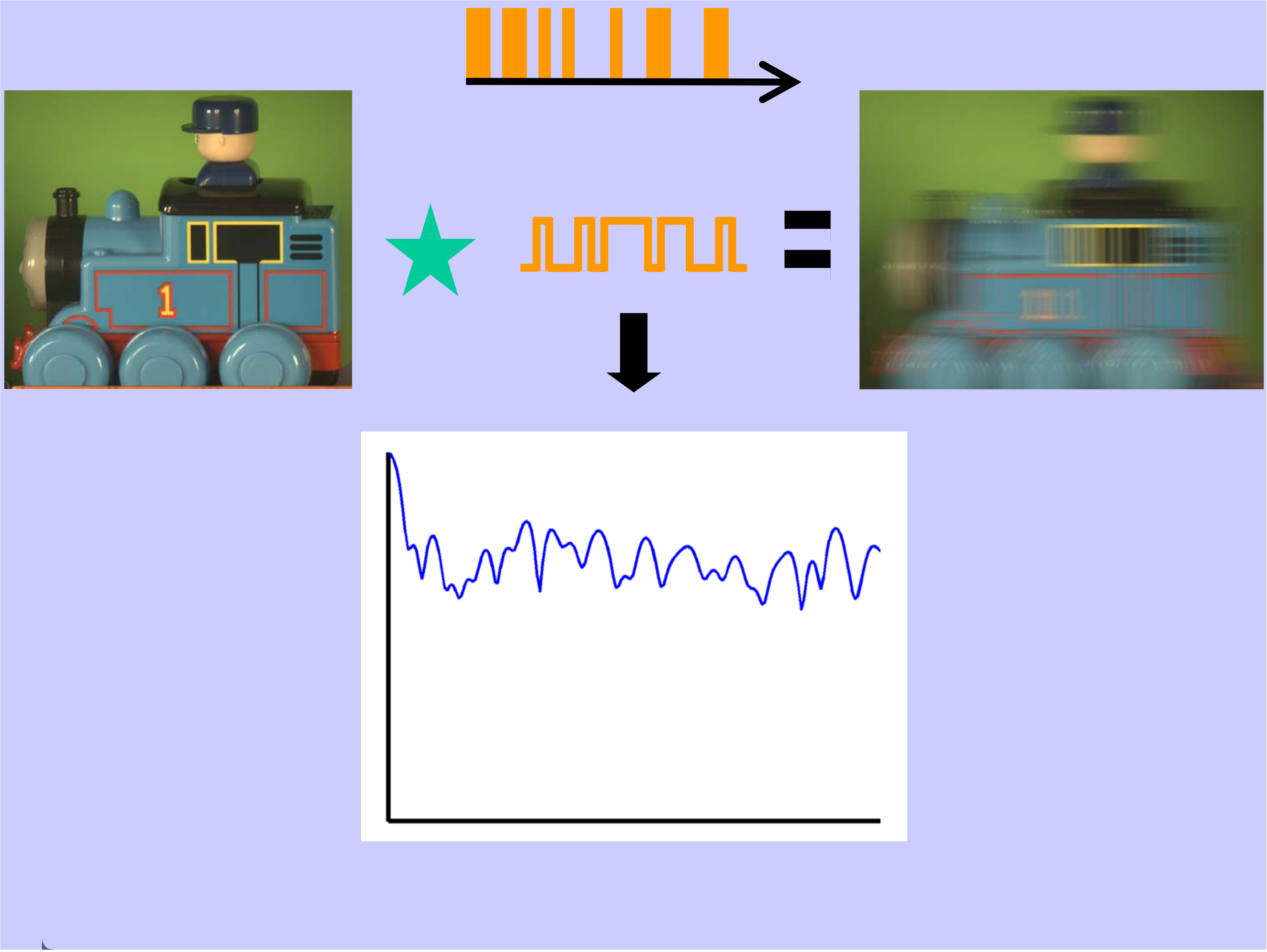
Coded Exposure Camera

Flutter shutter open and closed with a psuedo-random binary sequence within exposure duration to encode the blur

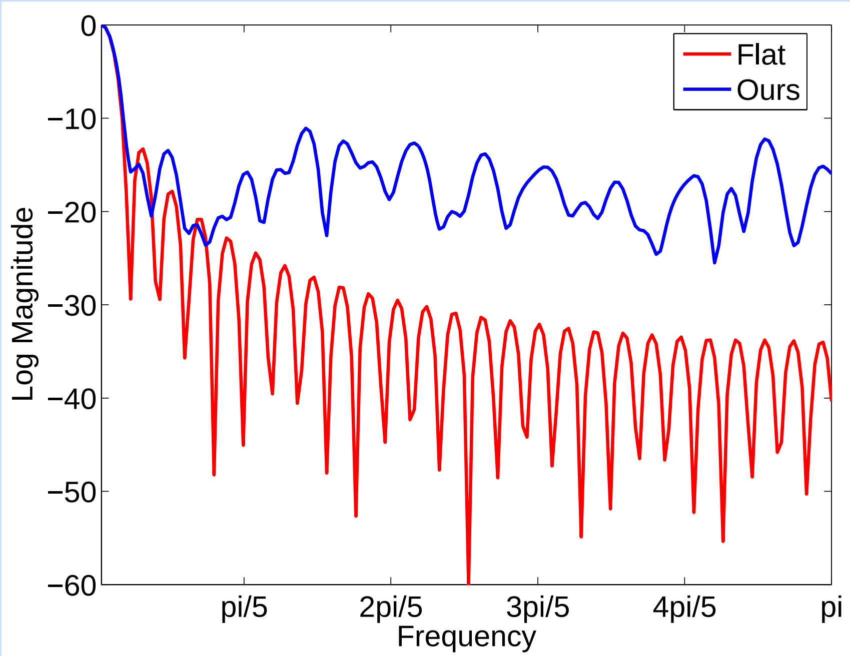
Short Exposure

Keep shutter open for very short duration. Avoids blur but image is dark and suffers from noise.

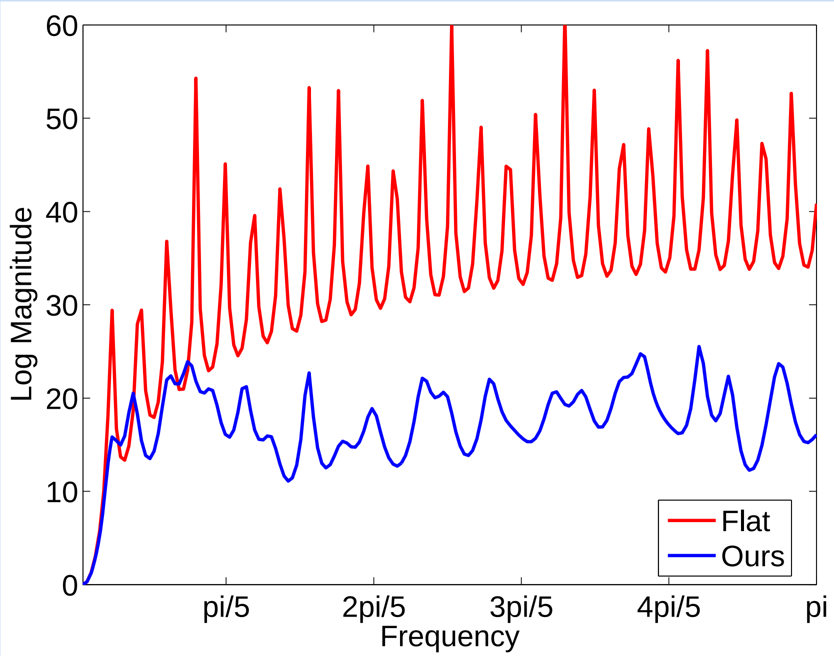




Coded Motion Blur = Preserves high spatial frequencies
= Deconvolution filter frequency response is nearly flat
= Deconvolution becomes a well-posed problem



Encoding Filter (Blurring)



Decoding Filter (Deblurring)


485-PCK

Defocus Blurred Photo

Digital Refocusing

Refocused Image on Person

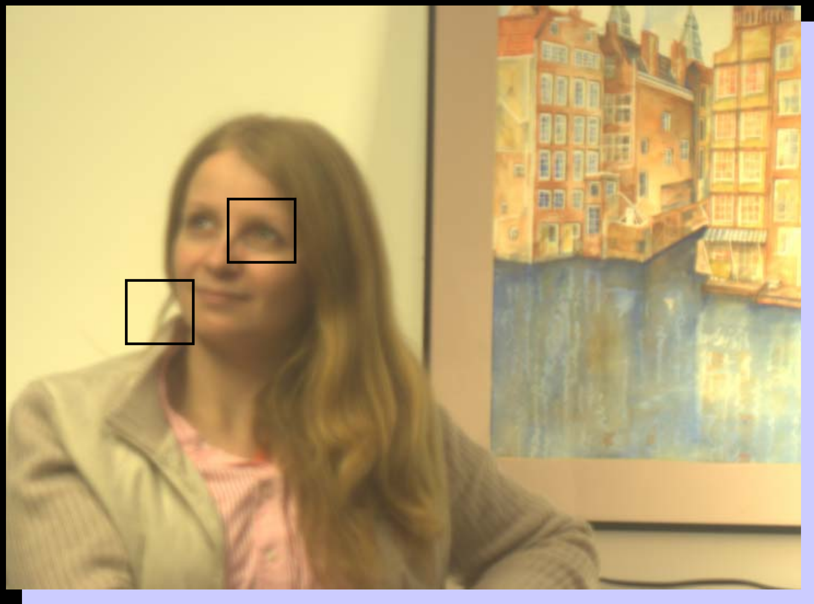
Coded Exposure

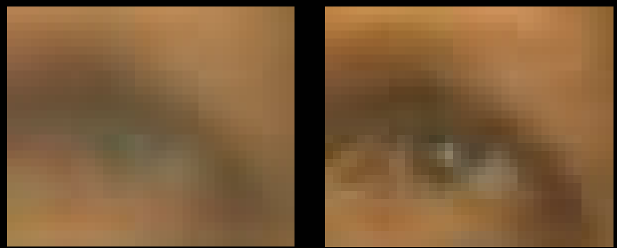
Temporal 1-D broadband code

Coded Aperture

Spatial 2-D broadband code

Digital Refocusing



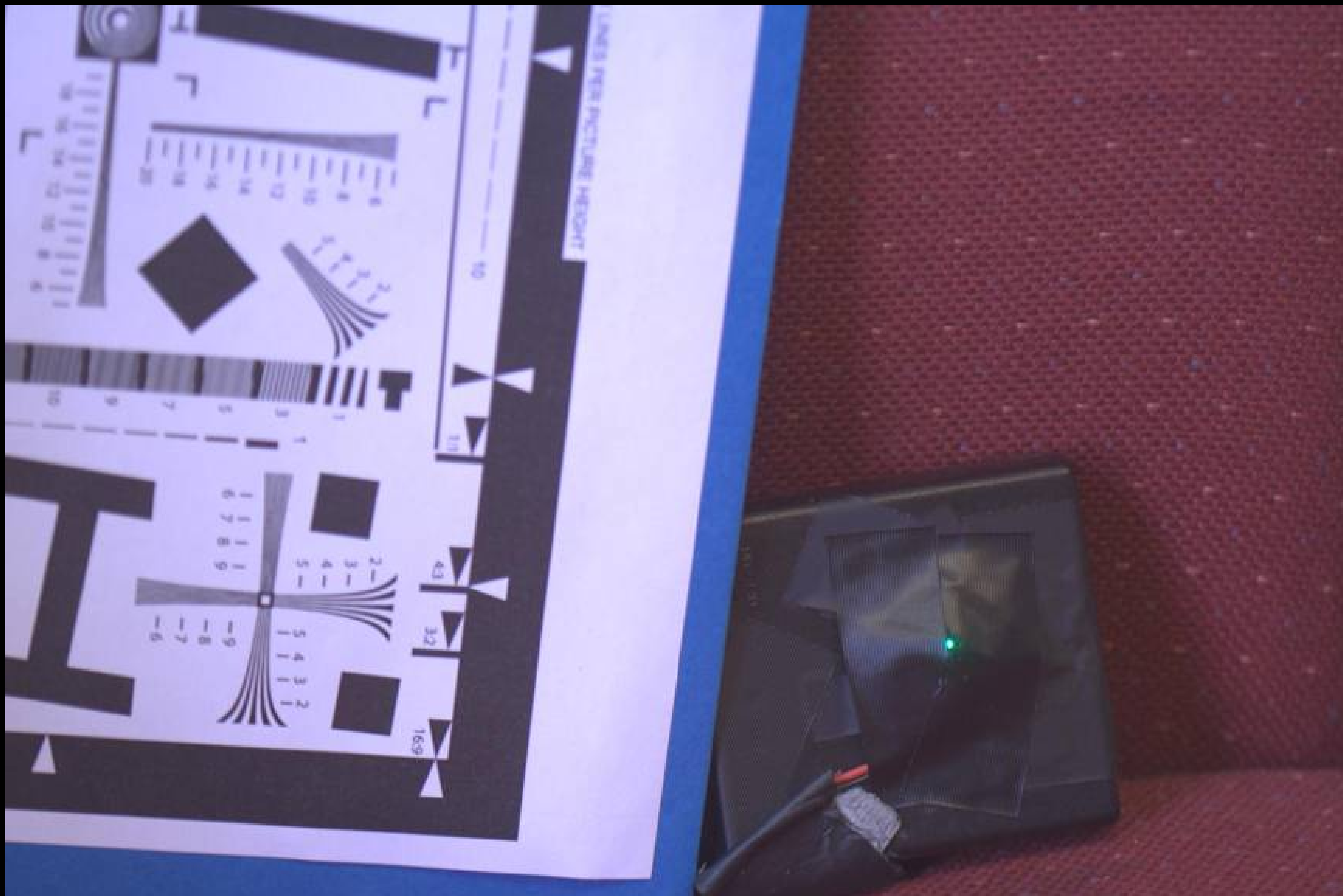


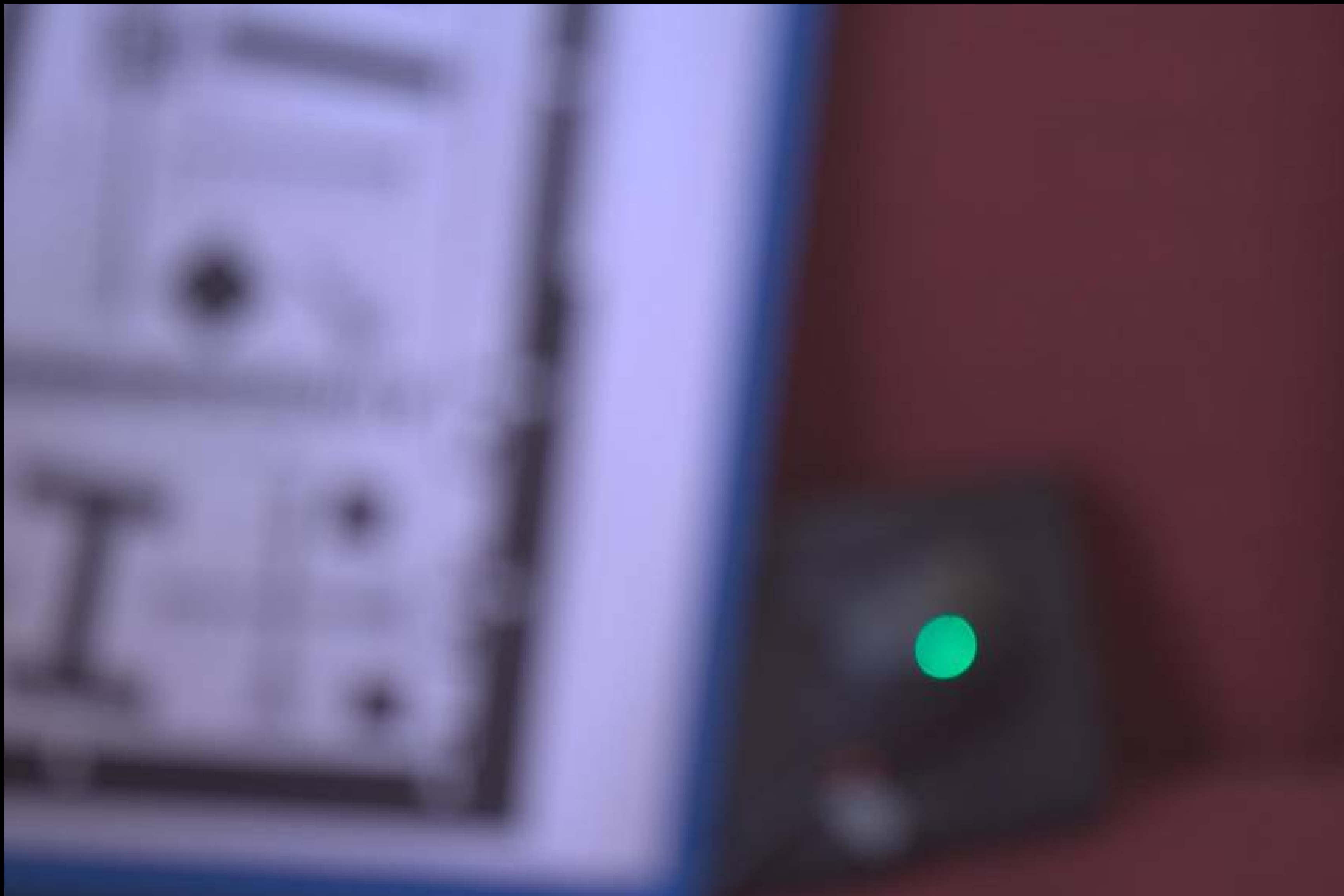
Coded Aperture Camera

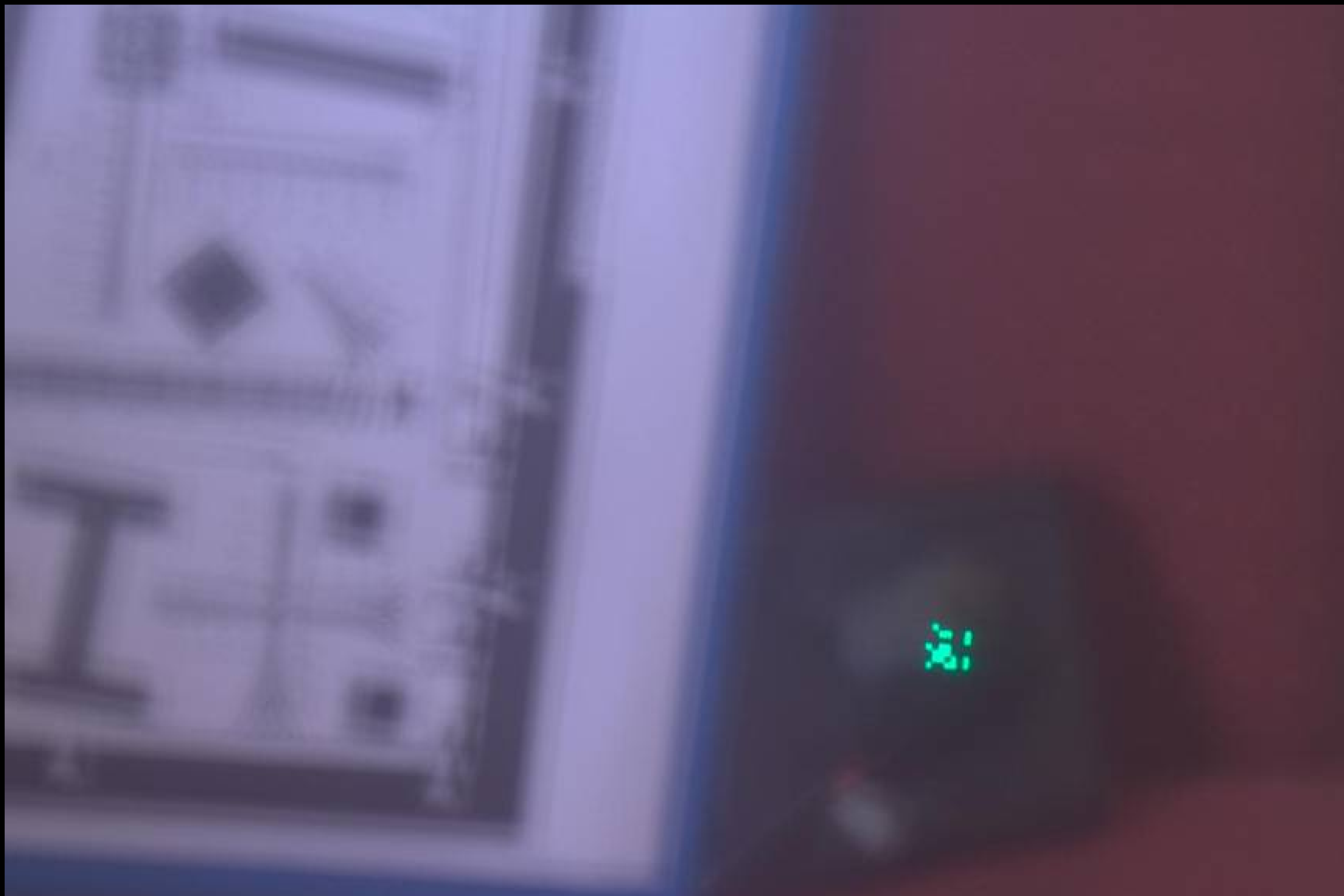
The aperture of a 100 mm lens is modified

Insert a coded mask with chosen binary pattern

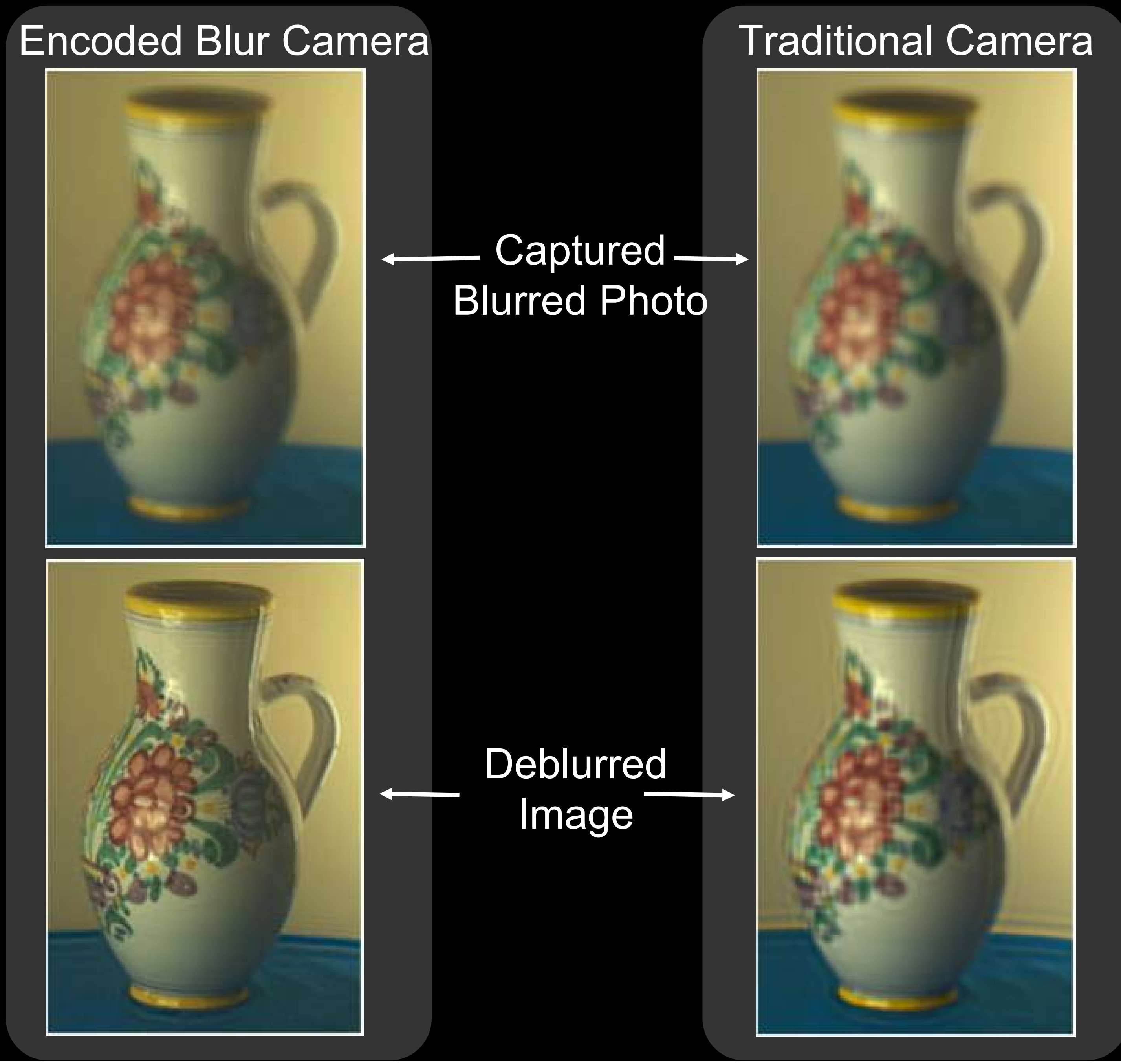
Rest of the camera is unmodified


LINES PER PICTURE HEIGHT





Comparison with Traditional Camera



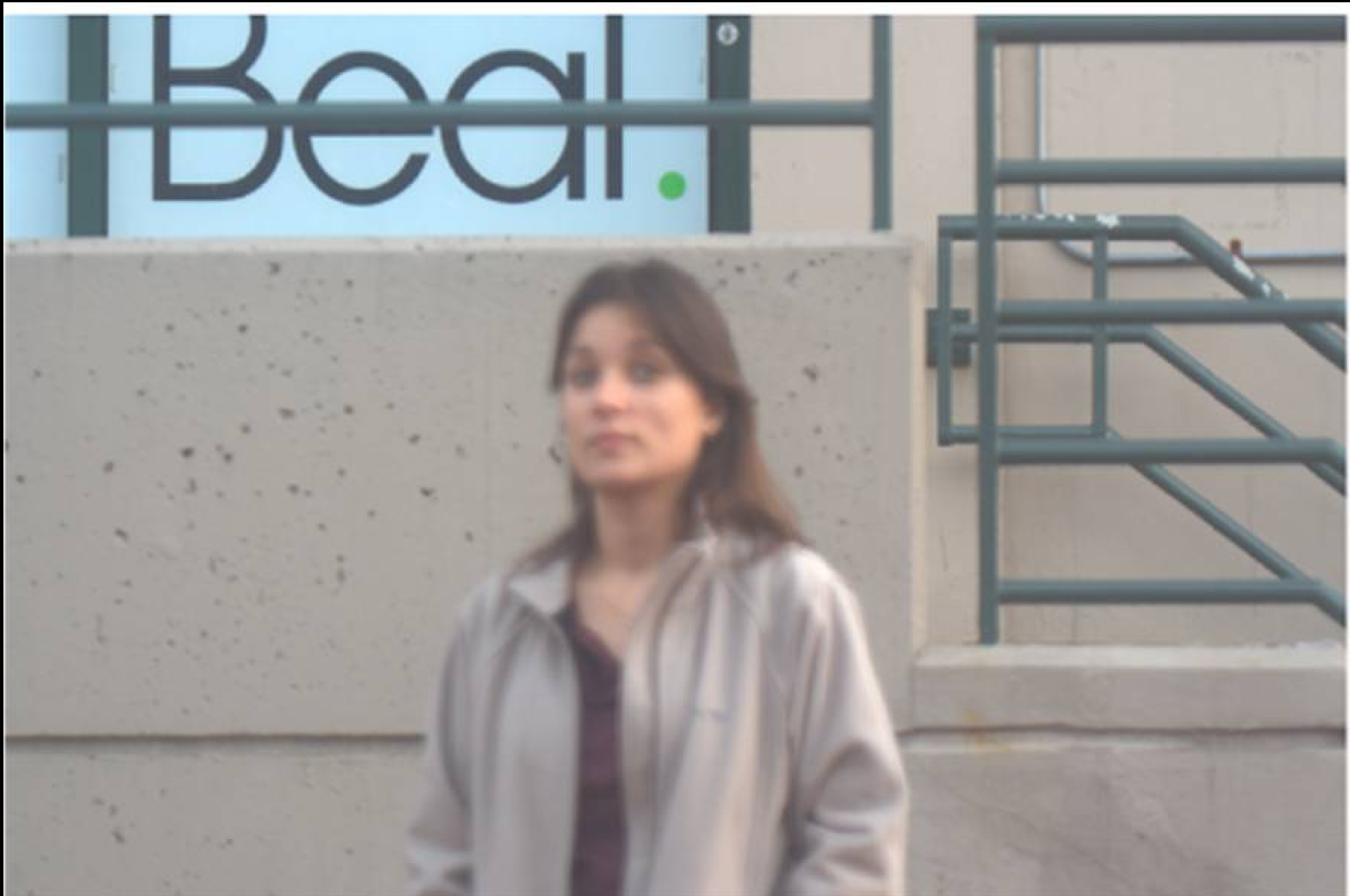
Comparison with Small Aperture Image

Small Aperture Image

Captured Blurred Image

Deblurred Image

Digital Refocusing

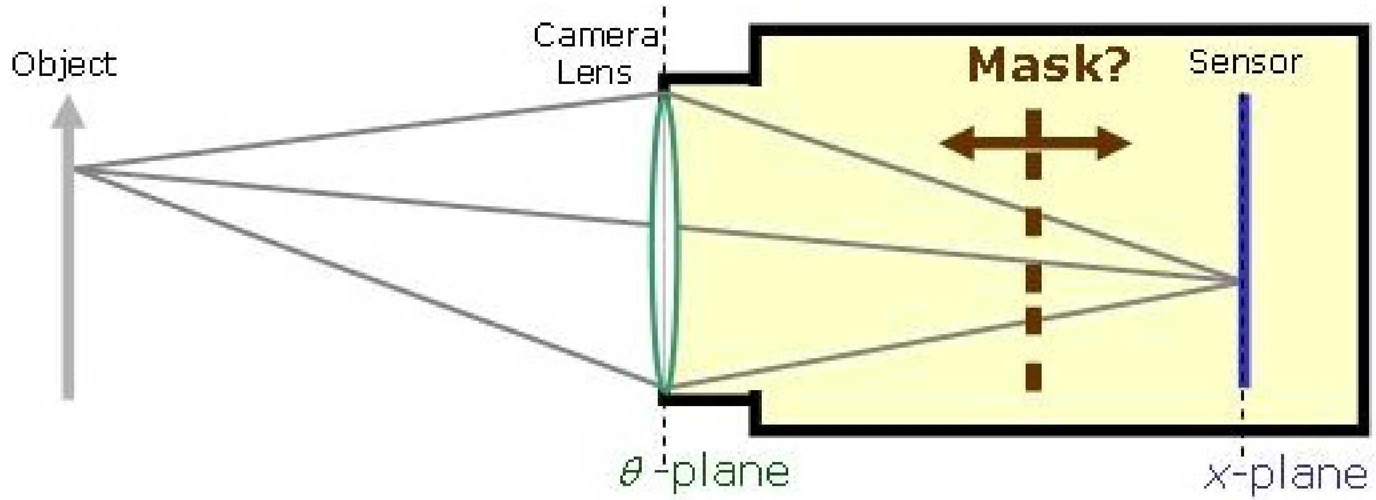


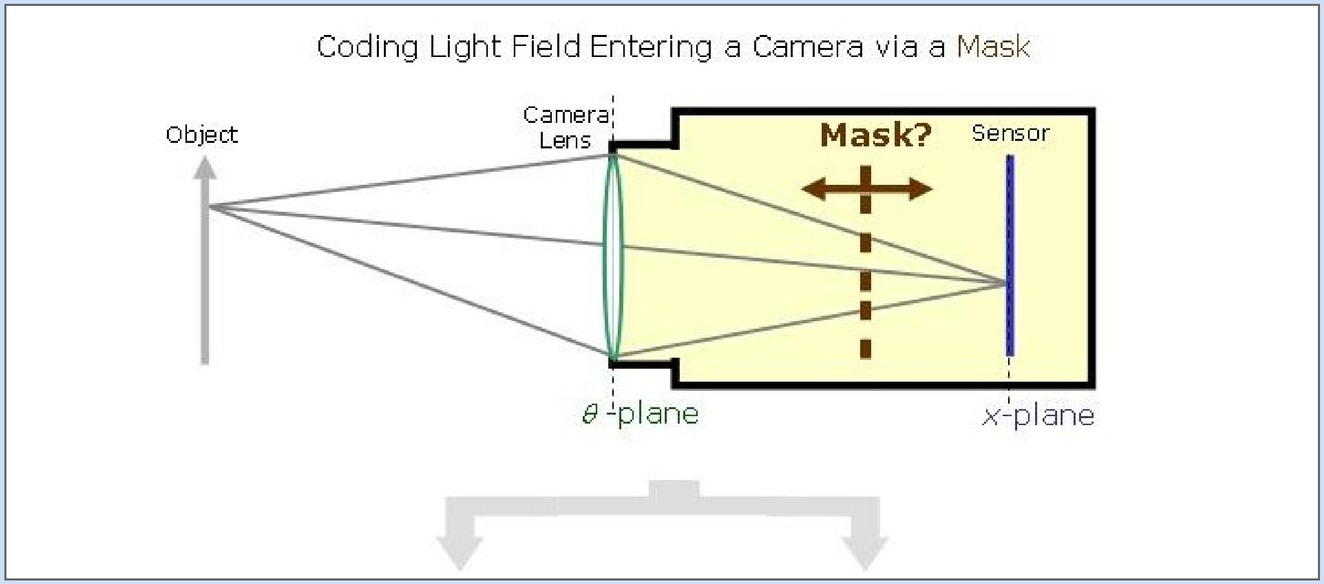
Captured Blurred Image

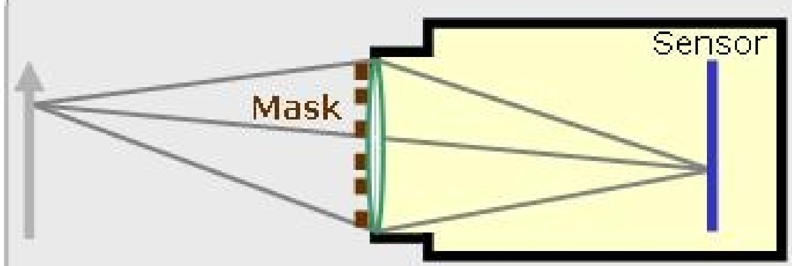
Digital Refocusing

Refocused Image on Person

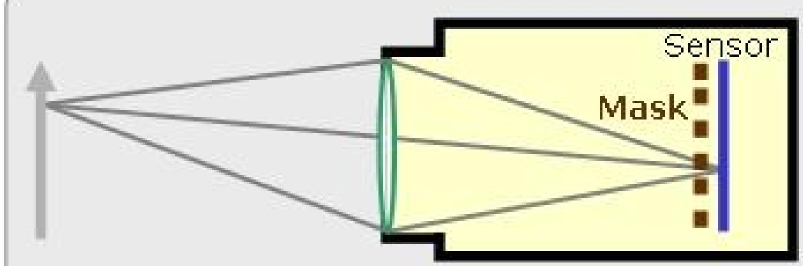
Can we capture more information by inserting a mask ?



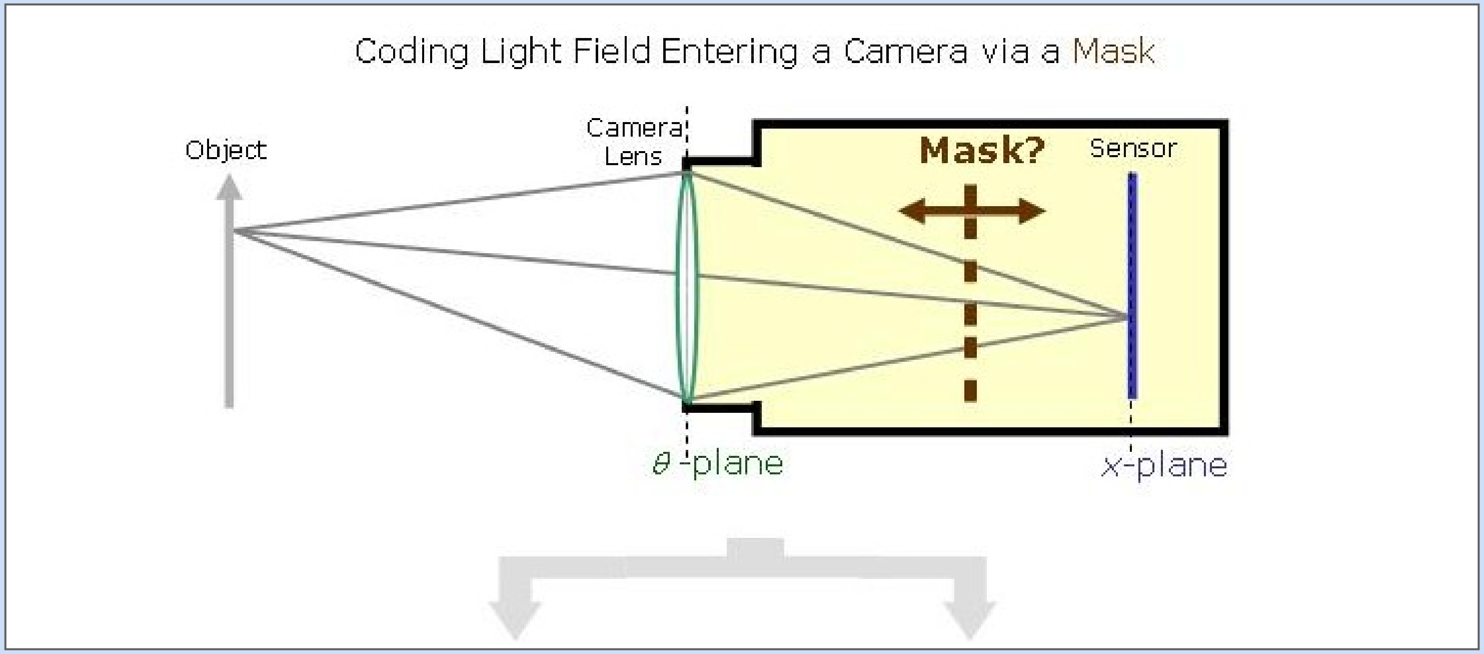


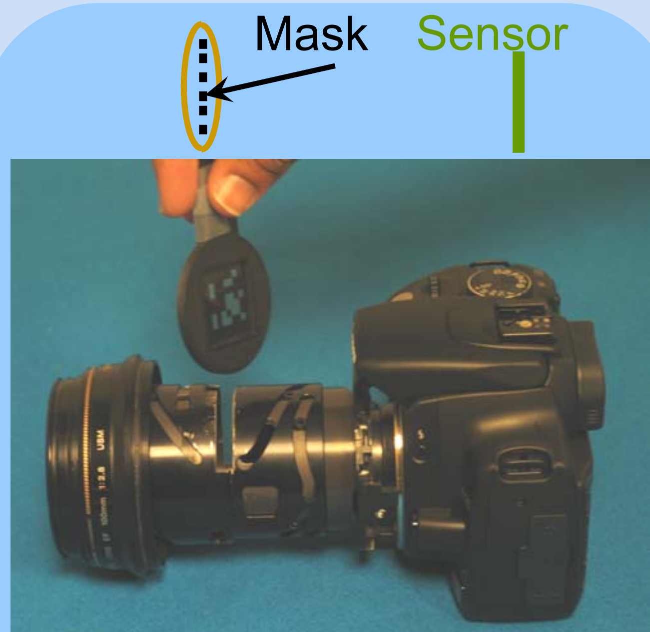


Encoded Blur Camera

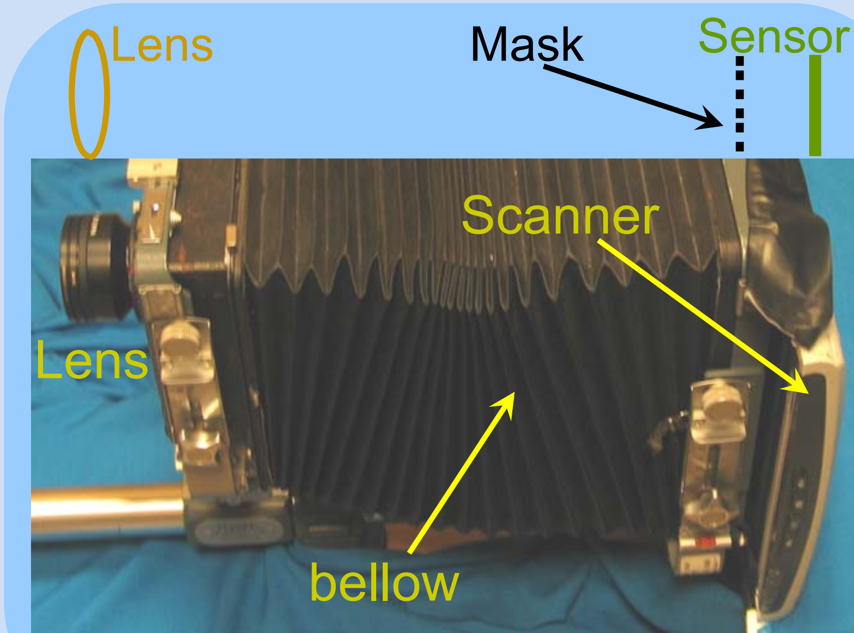


Heterodyne Light Field Camera



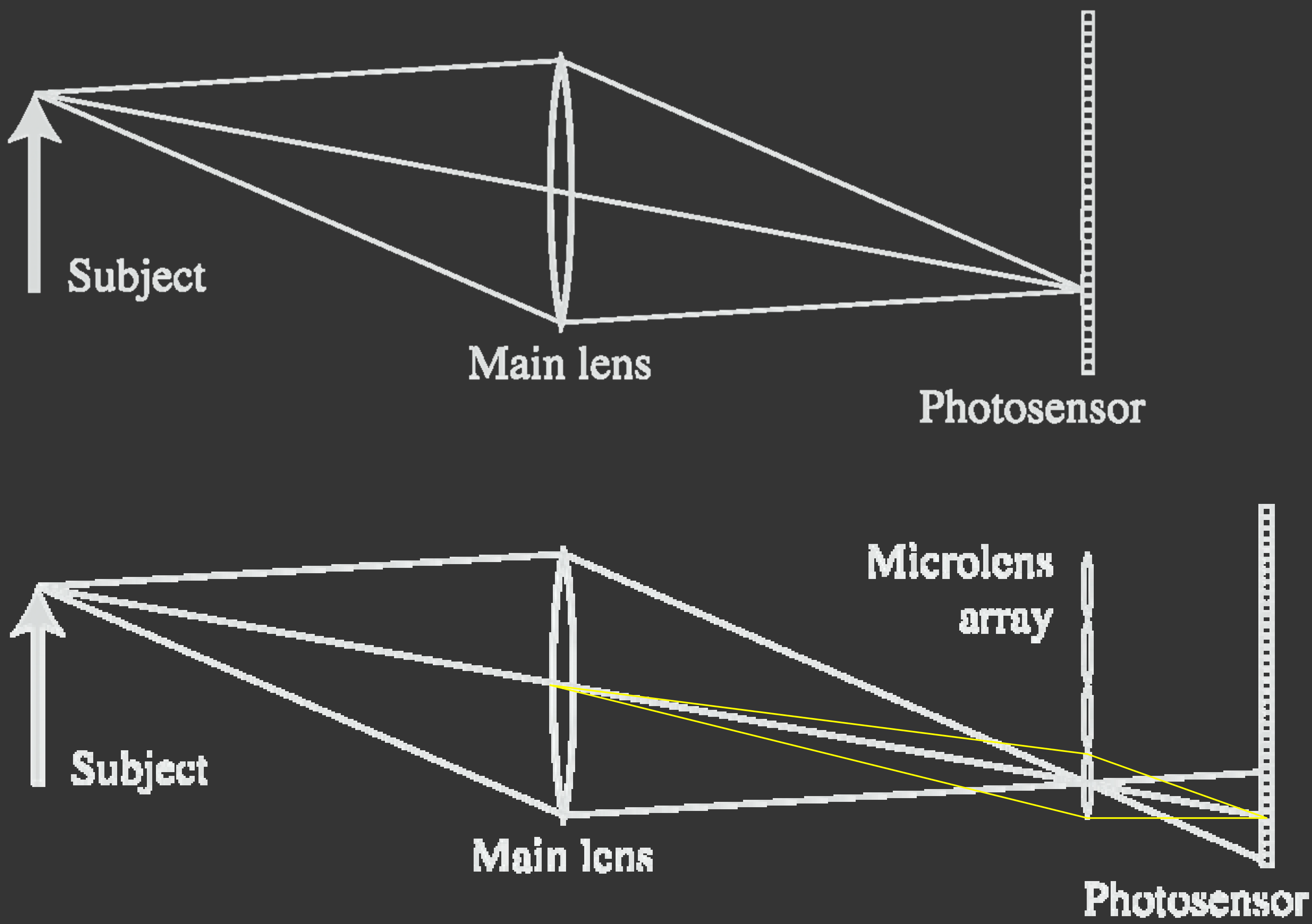


Encoded Blur Camera



Heterodyne Light Field Camera

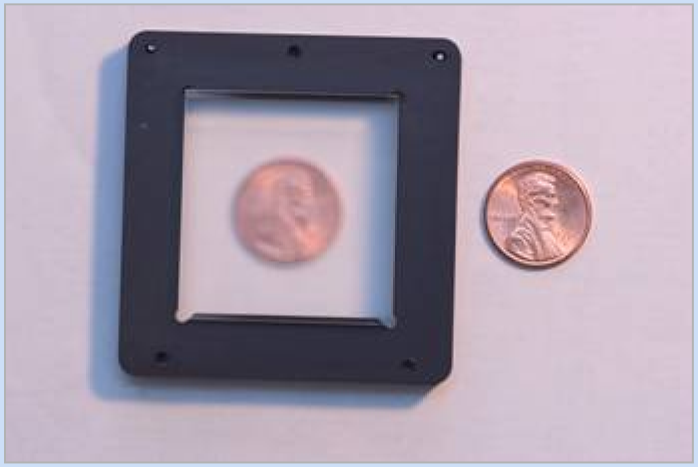
Lenslet-based Light Field camera

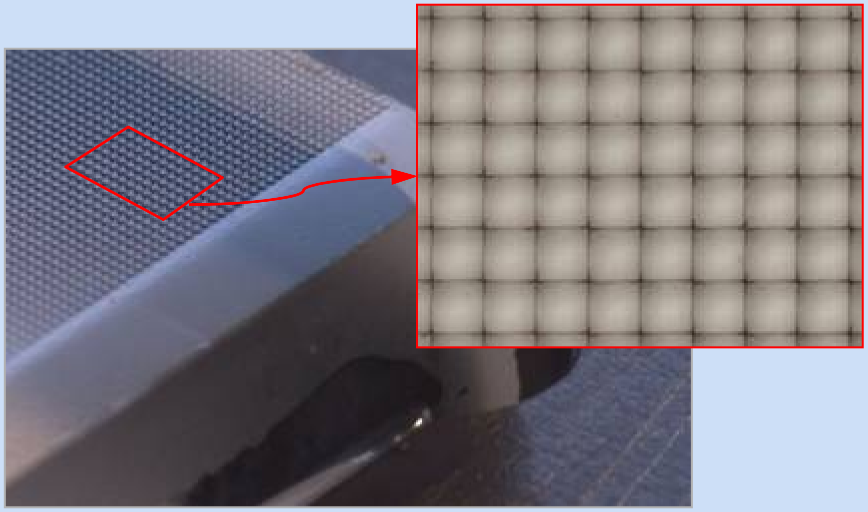


Stanford Plenoptic Camera [Ng et al 2005]

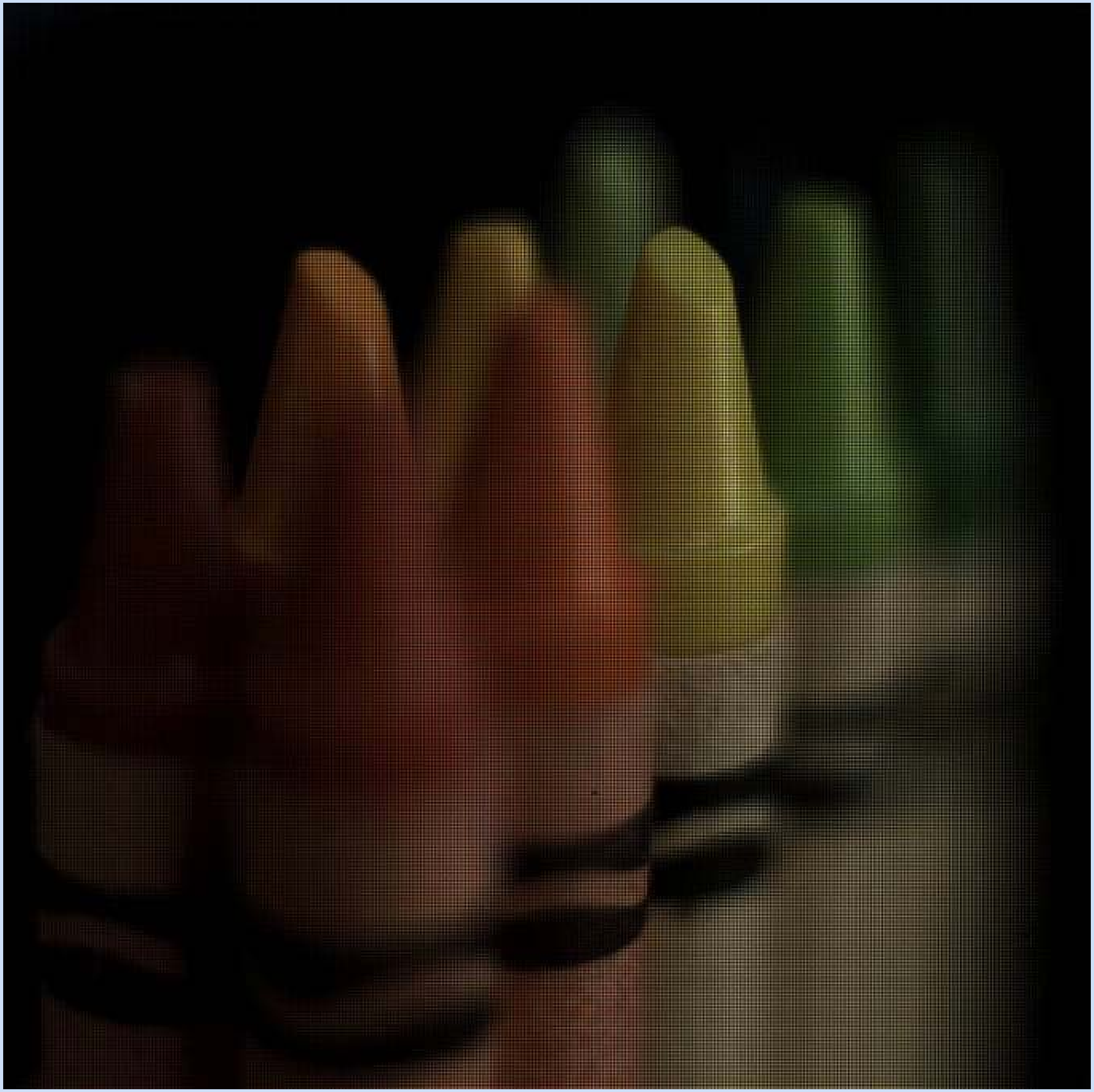
Contax medium format camera


Kodak 16-megapixel sensor


Adaptive Optics microlens array

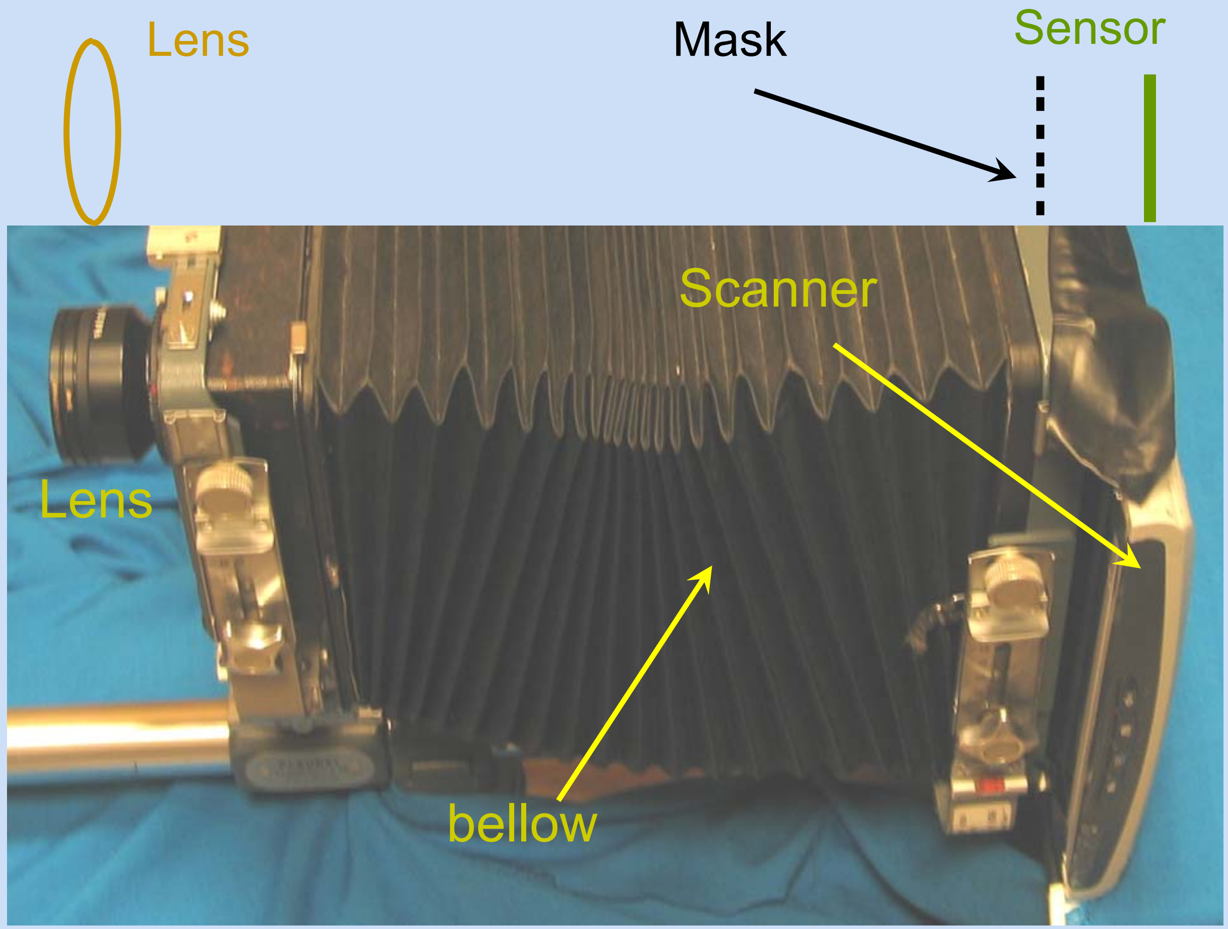

125μ square-sided microlenses

4000 × 4000 pixels ÷ 292 × 292 lenses = 14 × 14 pixels per lens



Digital Refocusing (Lenslet array)

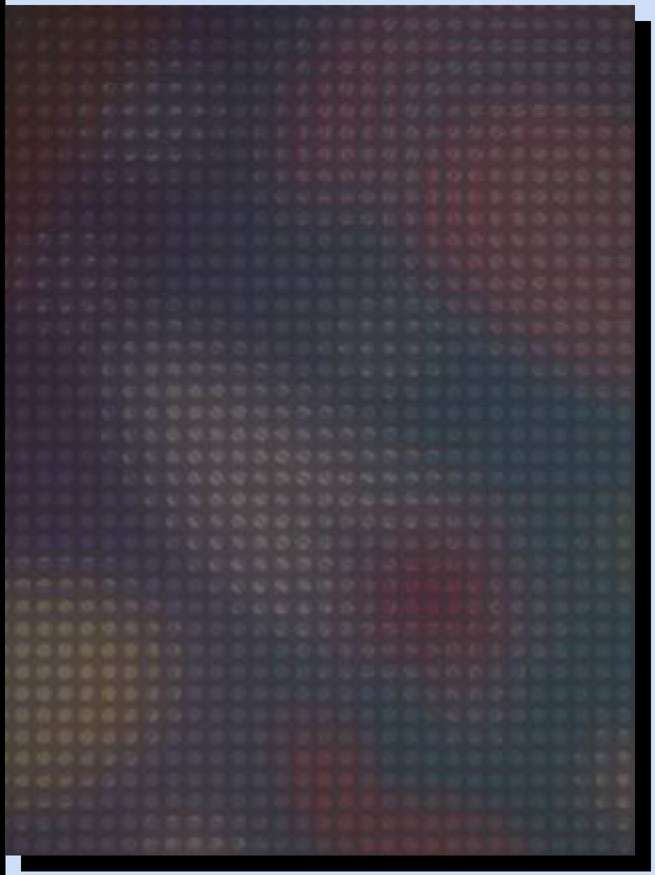
Heterodyne Light Field Camera



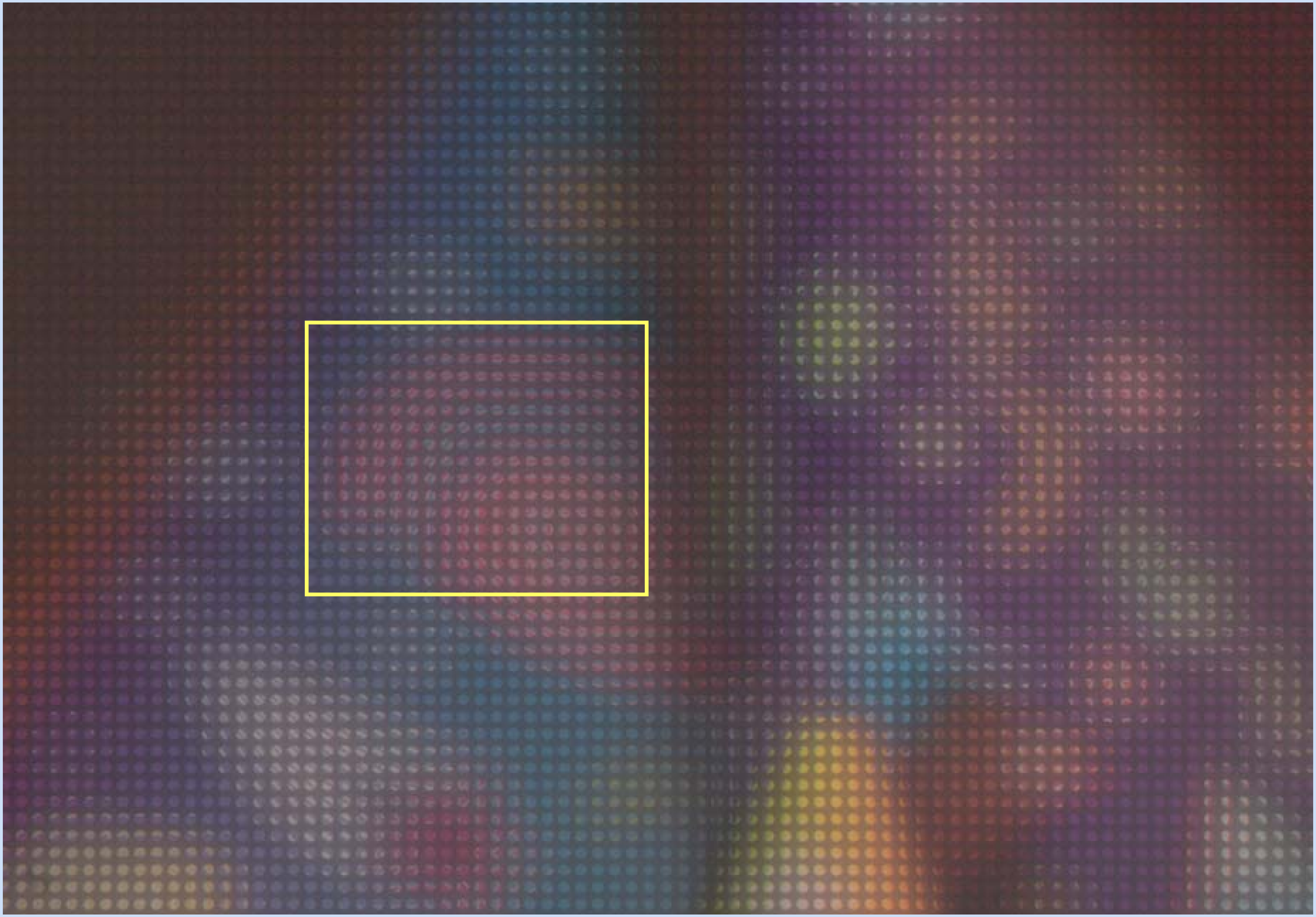
Canon flatbed scanner as the sensor.
Mask is is ~ 1 cm in front of the sensor.

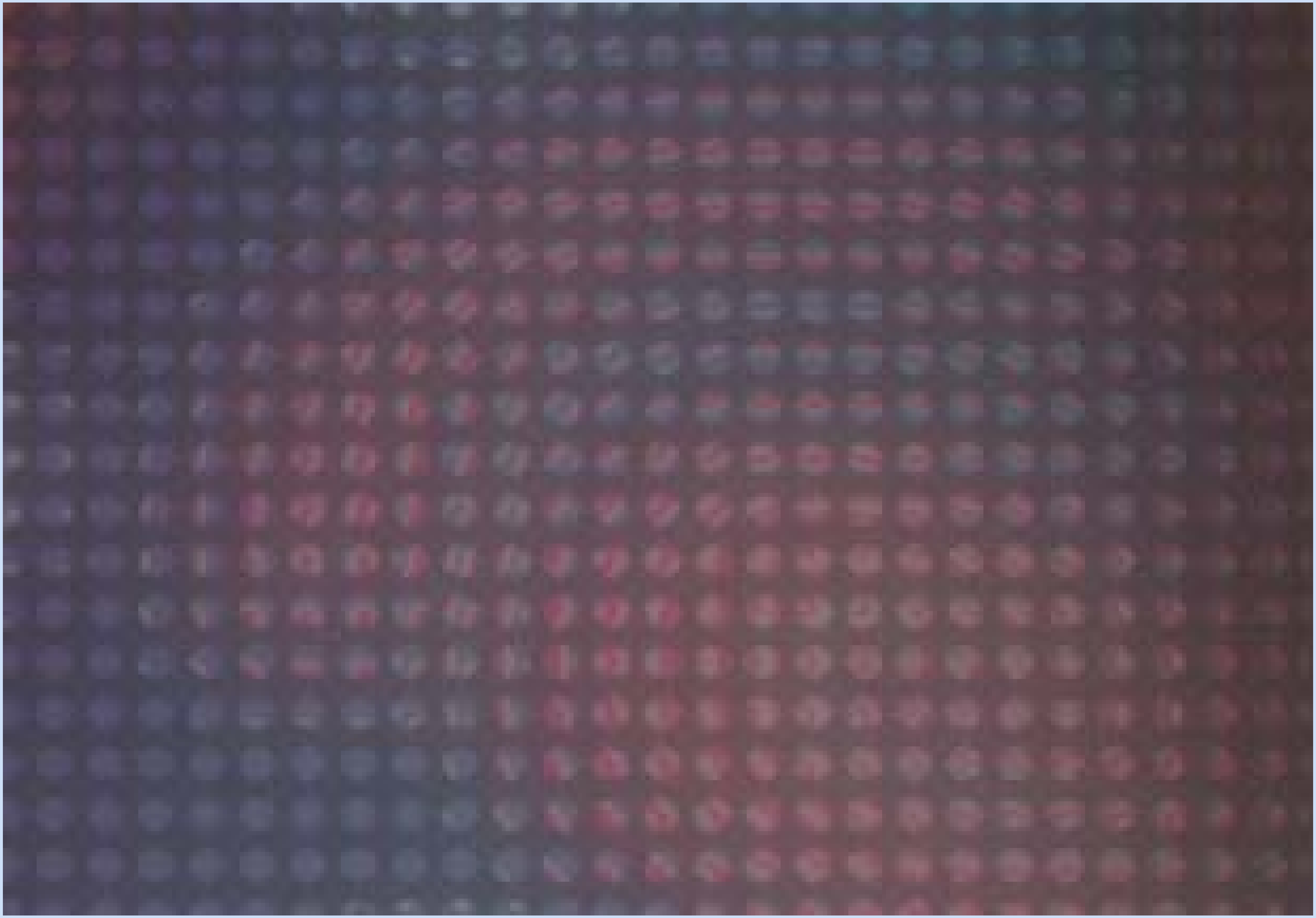
Capturing 4D light field

2D Sensor image

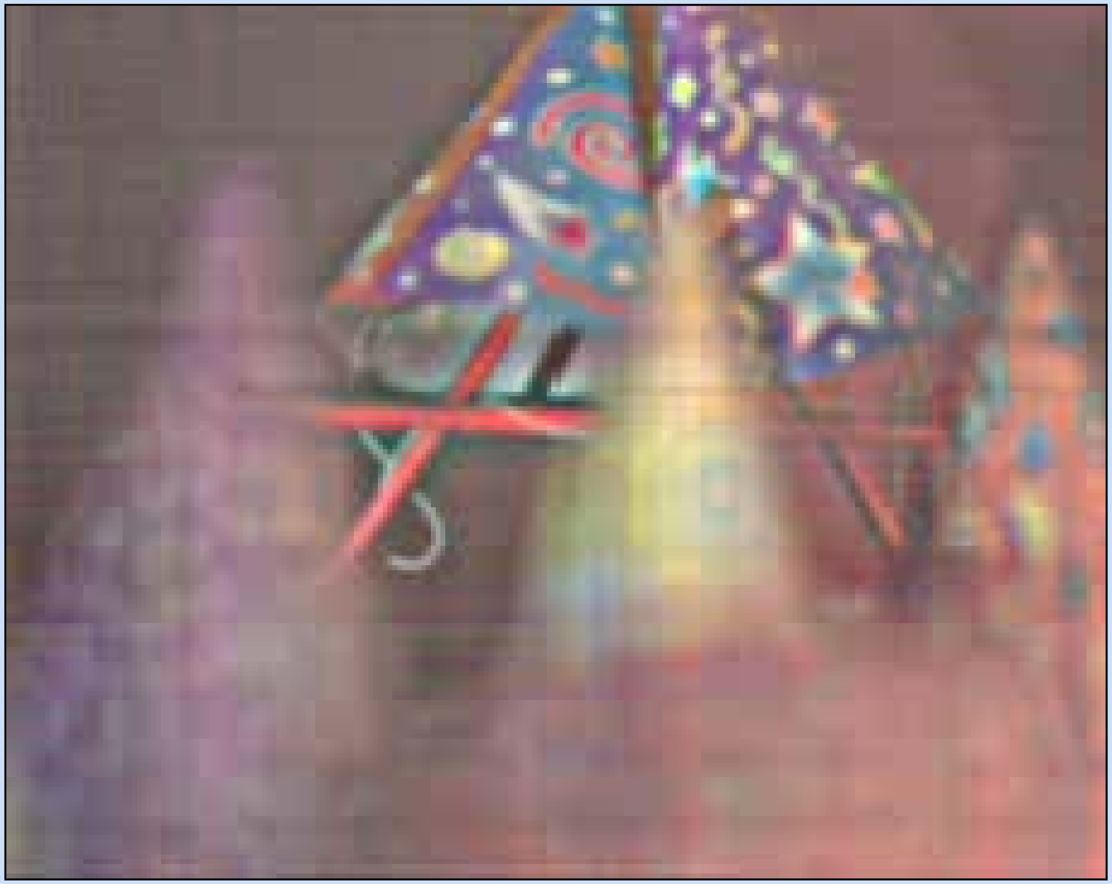


Zoom in showing
light field encoding





Movie:
Digital Refocusing by taking
2D Projections of 4D Light Field



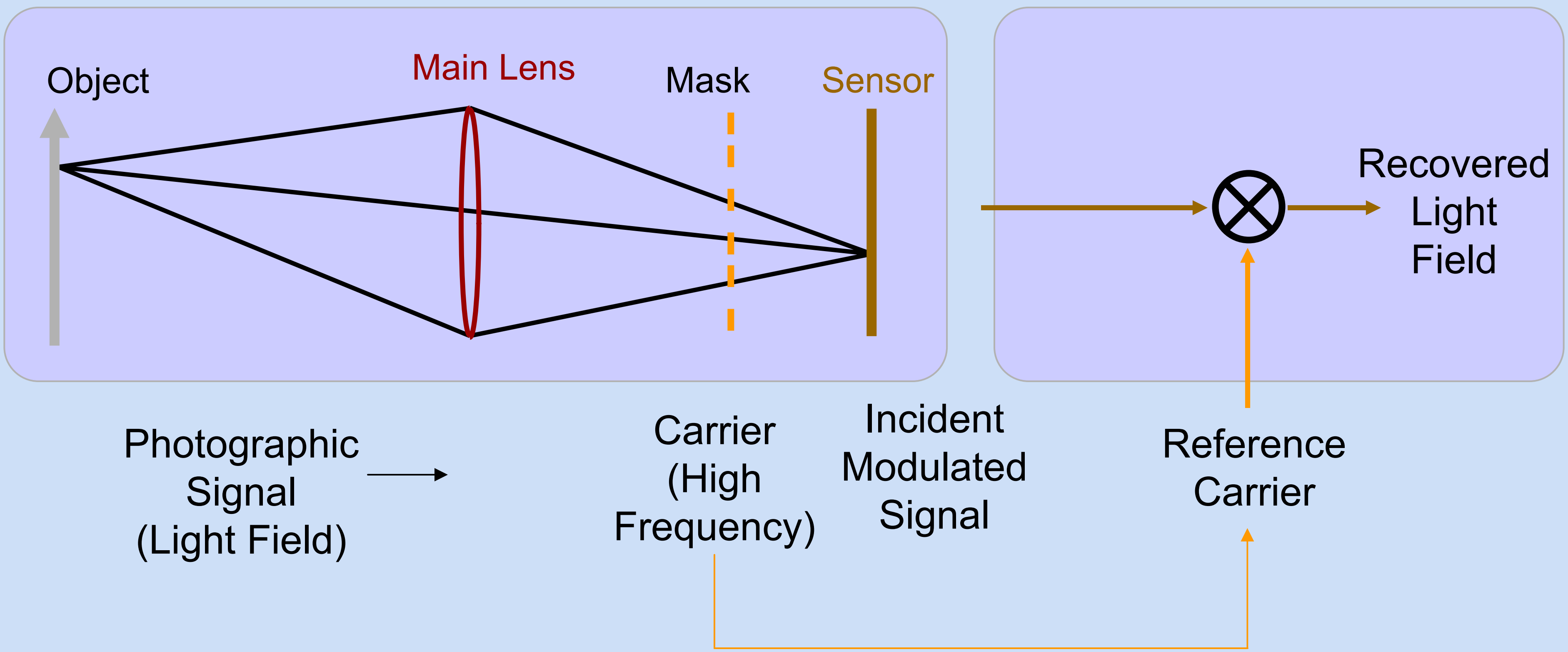
Movie:

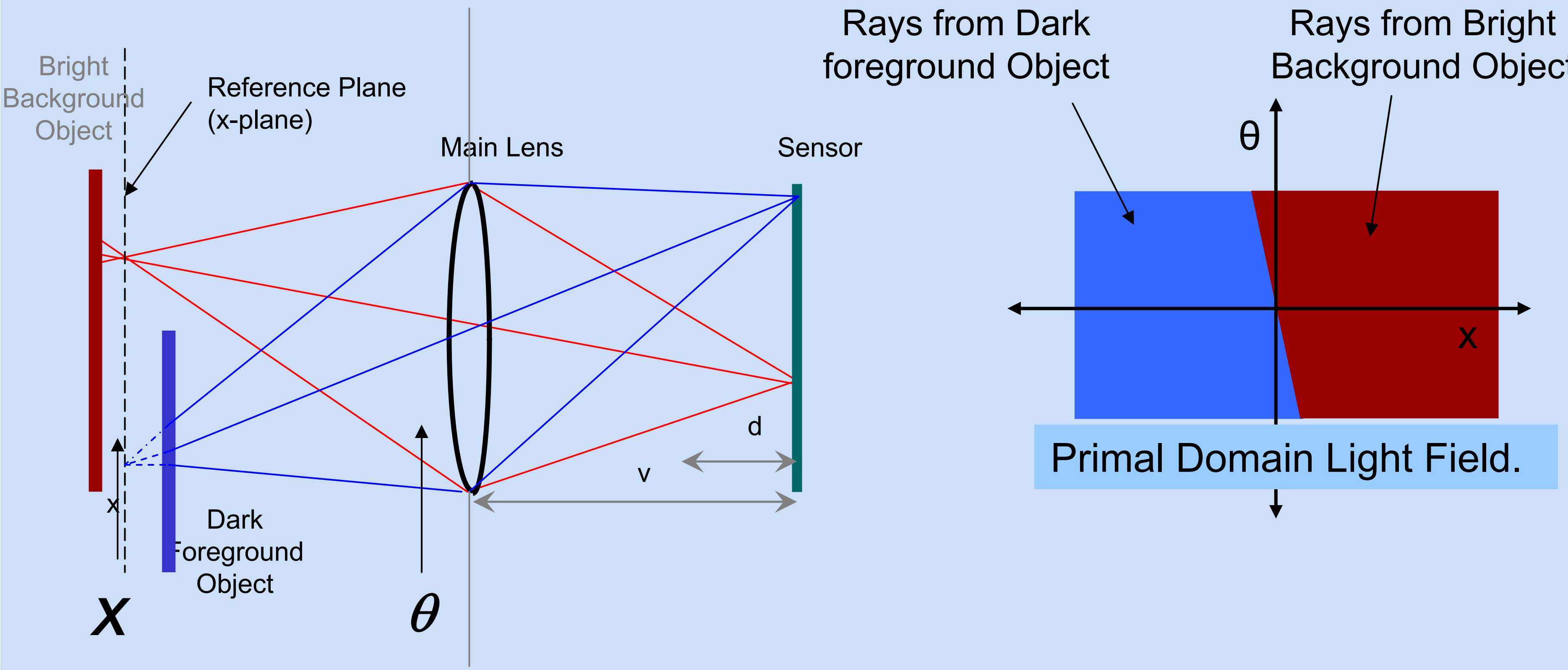
Different Views obtained from
2D Slices of 4D light field

How to Capture a 4D Signal with a 2D Sensor ?

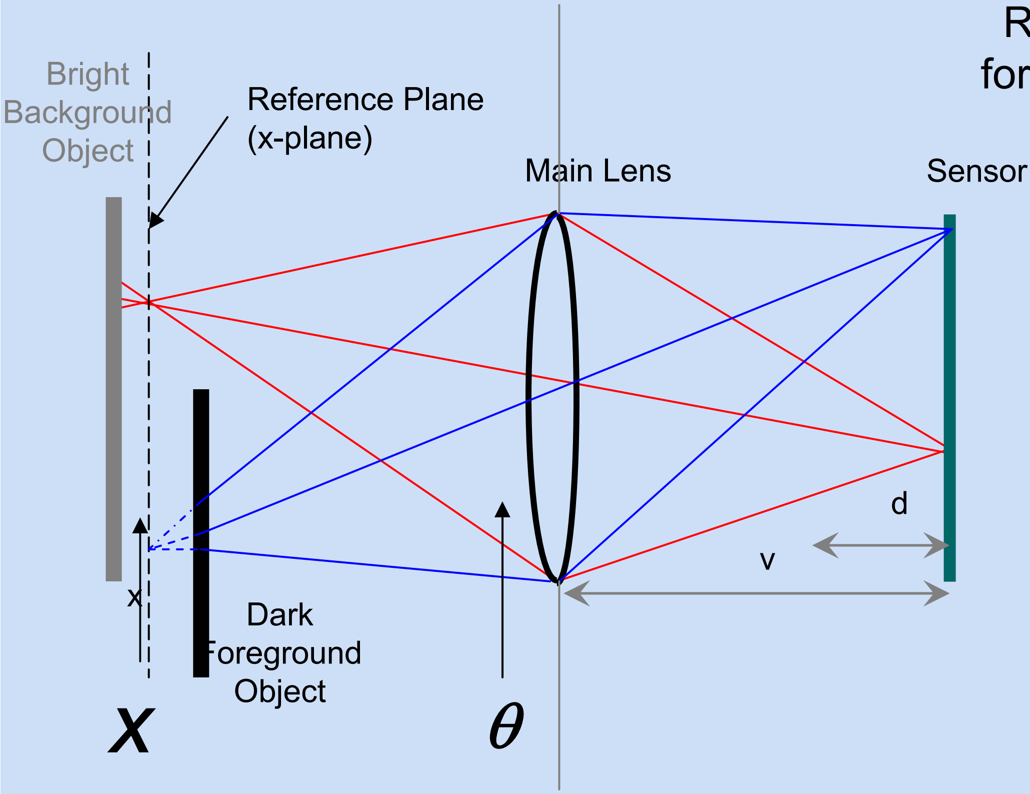
Mask-based Modulation

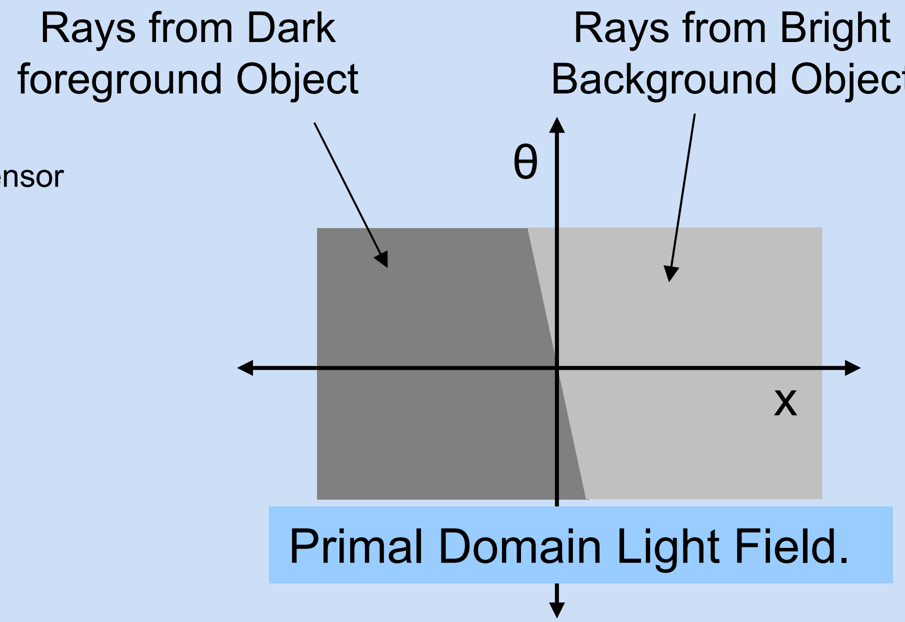
Software Demodulation

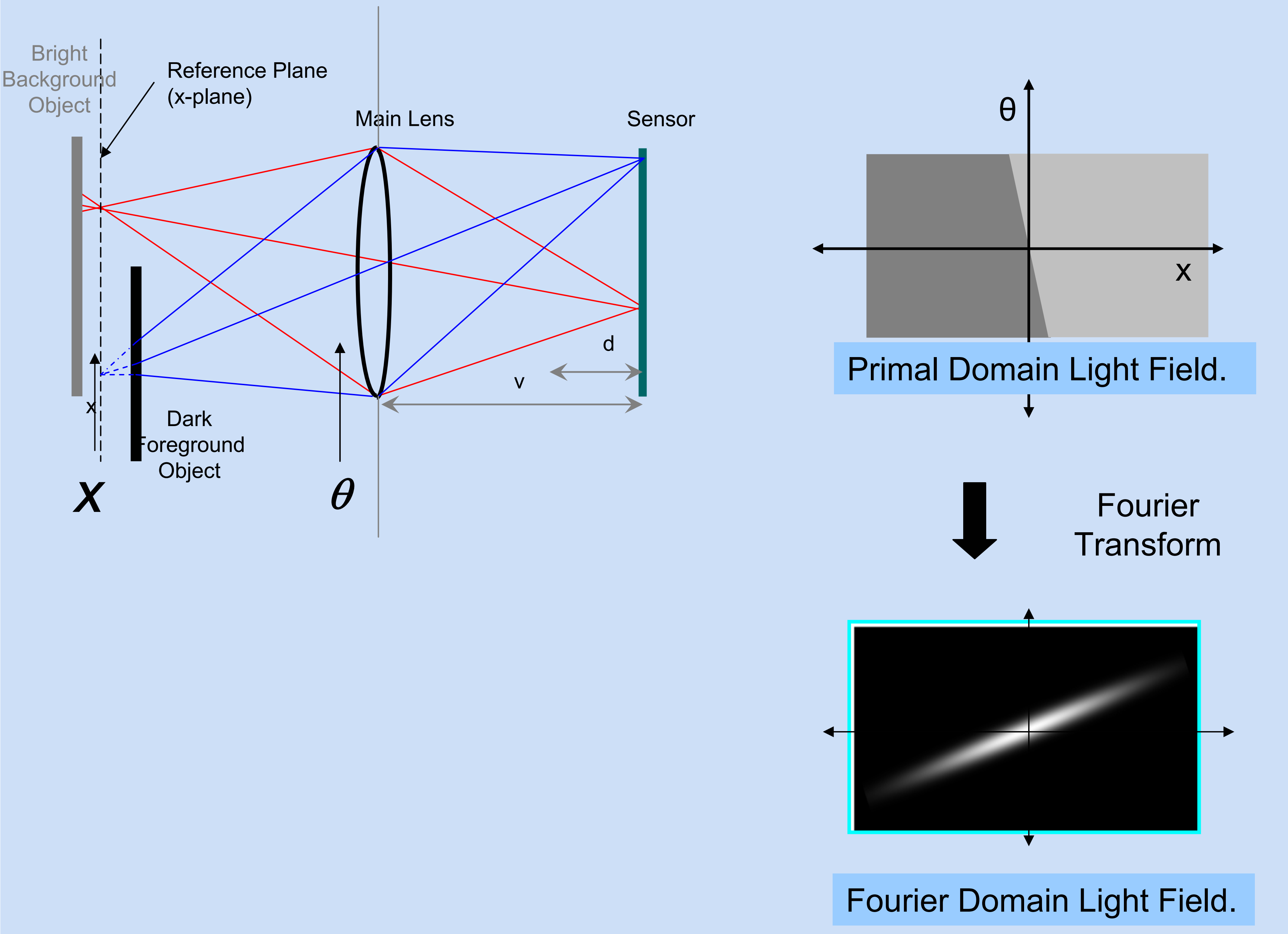




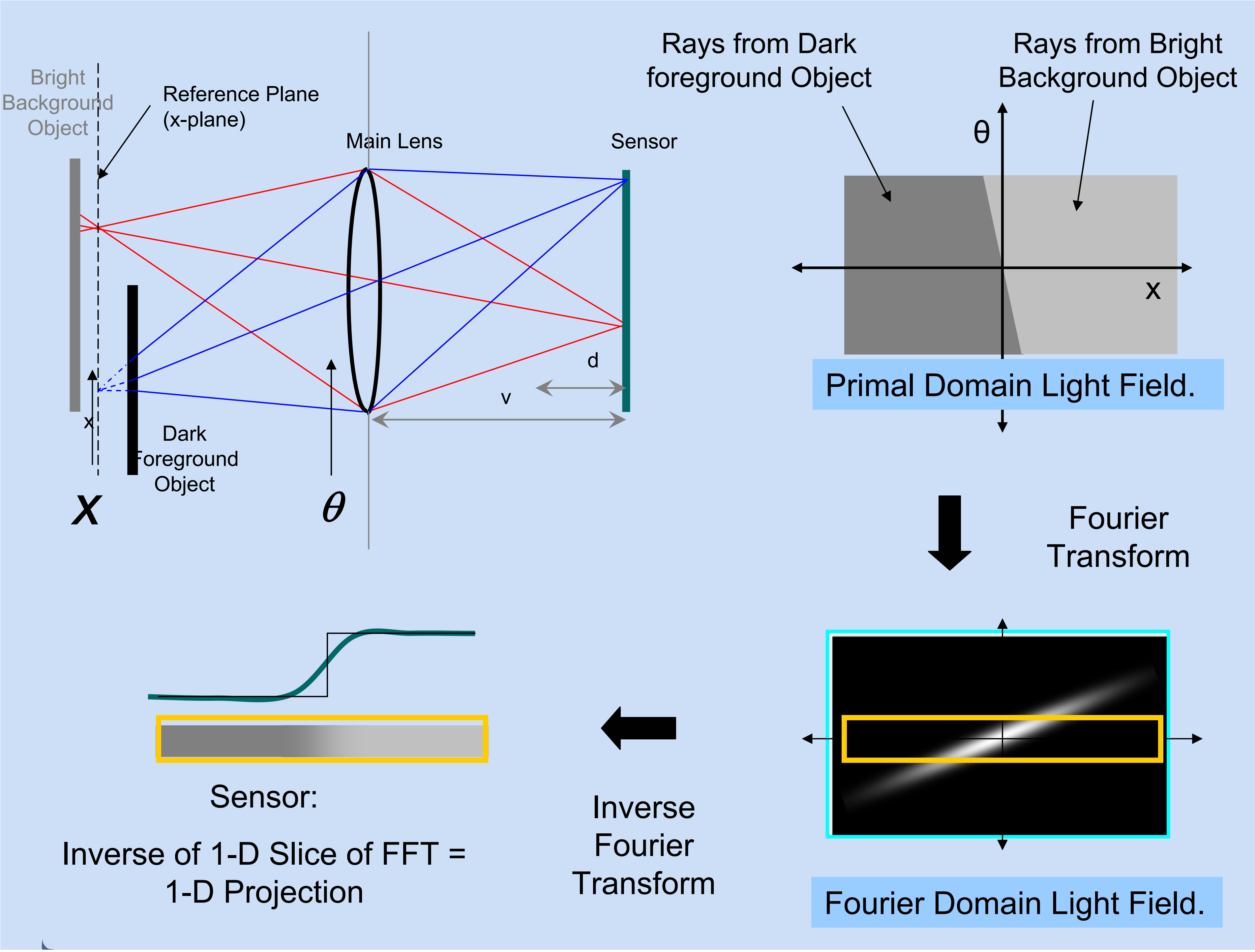
Bright Background Object
Reference Plane (x-plane)
Main Lens
Sensor
Rays from Dark foreground Object
Rays from Bright Background Object
θ
x
d
v
x
Dark Foreground Object
X
θ
Primal Domain Light Field.

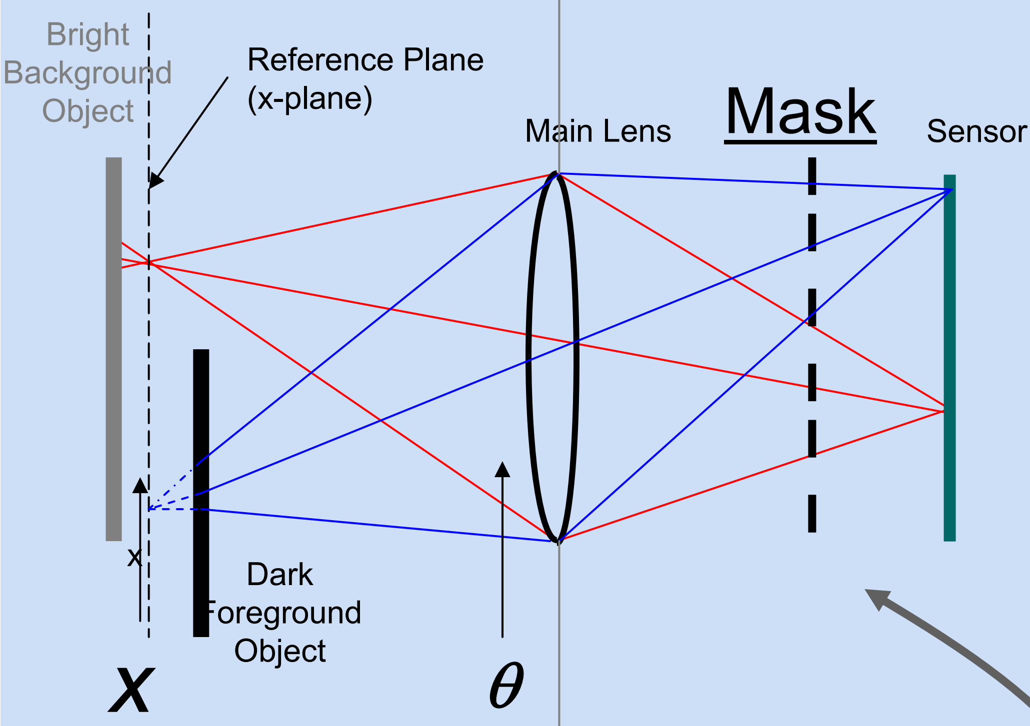

Bright Background Object
Reference Plane (x-plane)
Main Lens
Sensor
d
v
x
Dark Foreground Object
X
θ


Rays from Dark foreground Object
Rays from Bright Background Object
θ
x
Primal Domain Light Field.



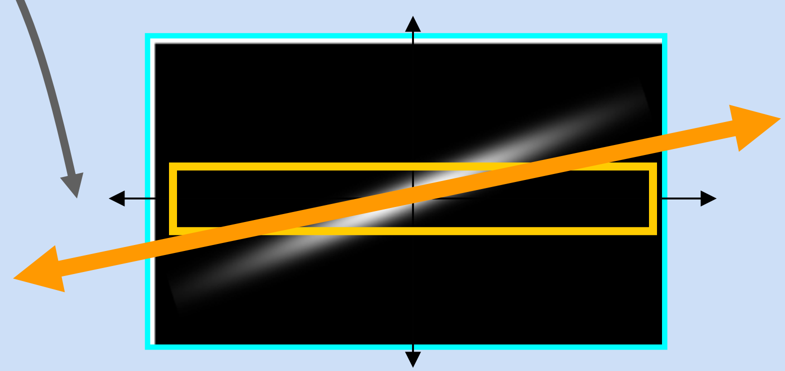
Bright Background Object
Reference Plane (x-plane)
Main Lens
Sensor
d
v
x
Dark Foreground Object
X
θ
θ
x
Primal Domain Light Field.
Fourier Transform
Fourier Domain Light Field.


Bright
Background
Object
Reference Plane
(x-plane)
Main Lens
Sensor
d
v
x
Dark
Foreground
Object
X
θ
Rays from Dark
foreground Object
Rays from Bright
Background Object
θ
x
Primal Domain Light Field.
Fourier
Transform
Fourier Domain Light Field.
Inverse
Fourier
Transform
Sensor:
Inverse of 1-D Slice of FFT =
1-D Projection



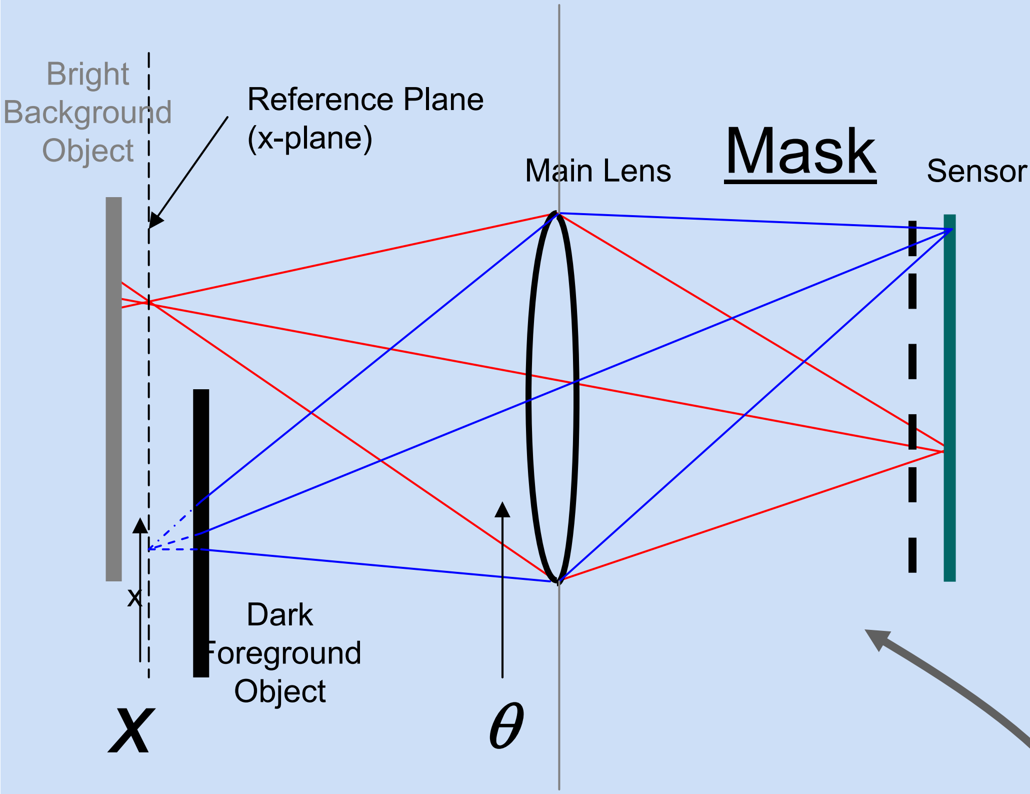
Incident Light Field = Multiplication with the Light Field of the mask

Fourier Transform

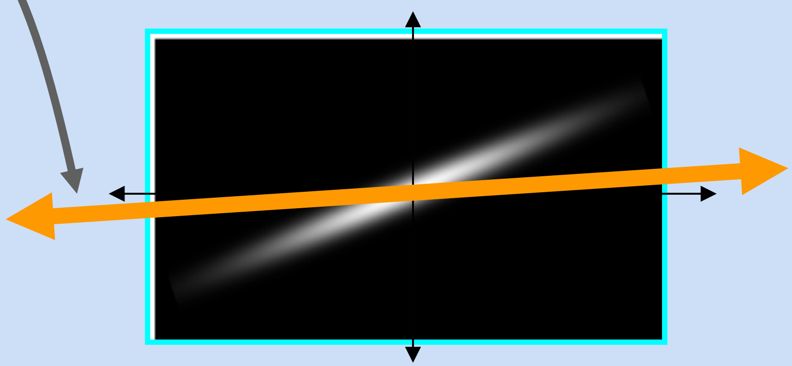


Convolution with the Fourier transform of the Mask

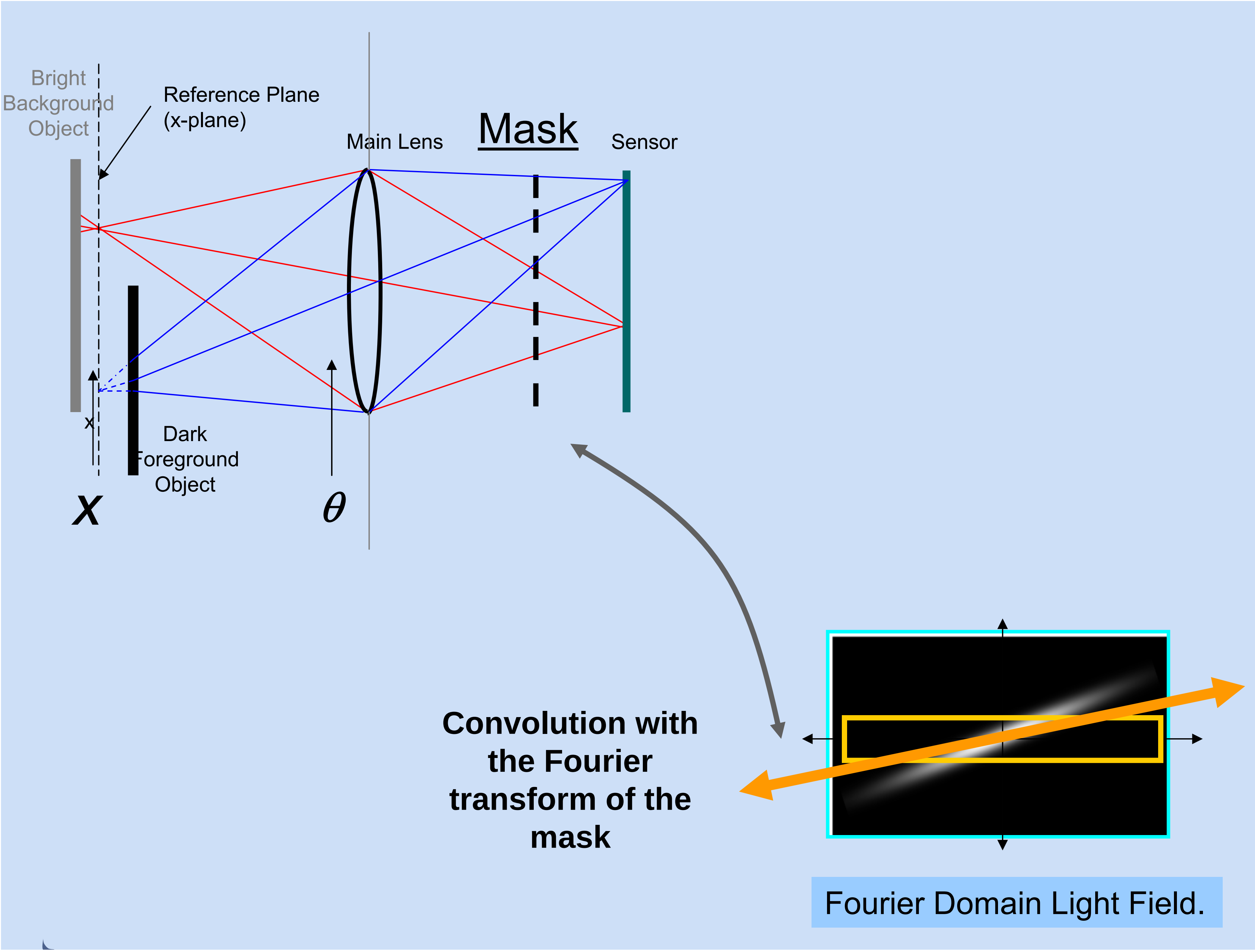
Fourier Domain Light Field.

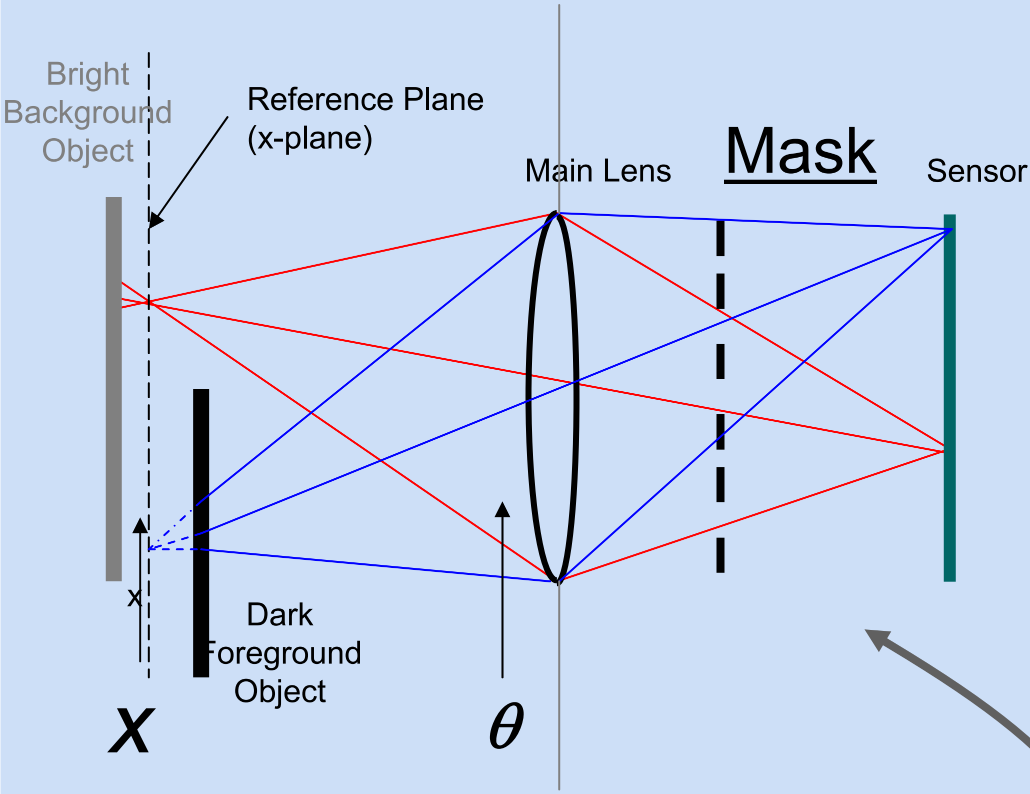


Convolution with the Fourier transform of the mask

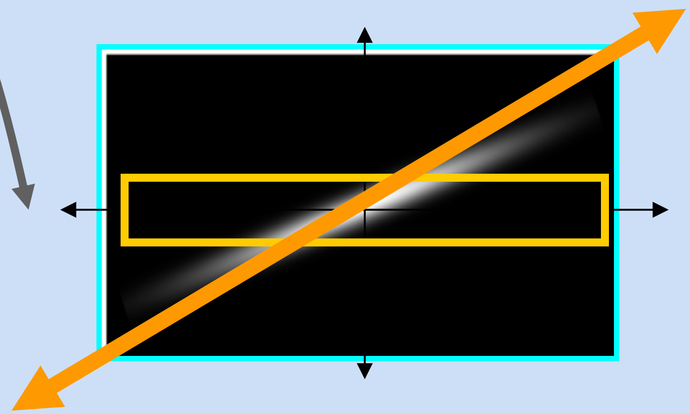


Fourier Domain Light Field.

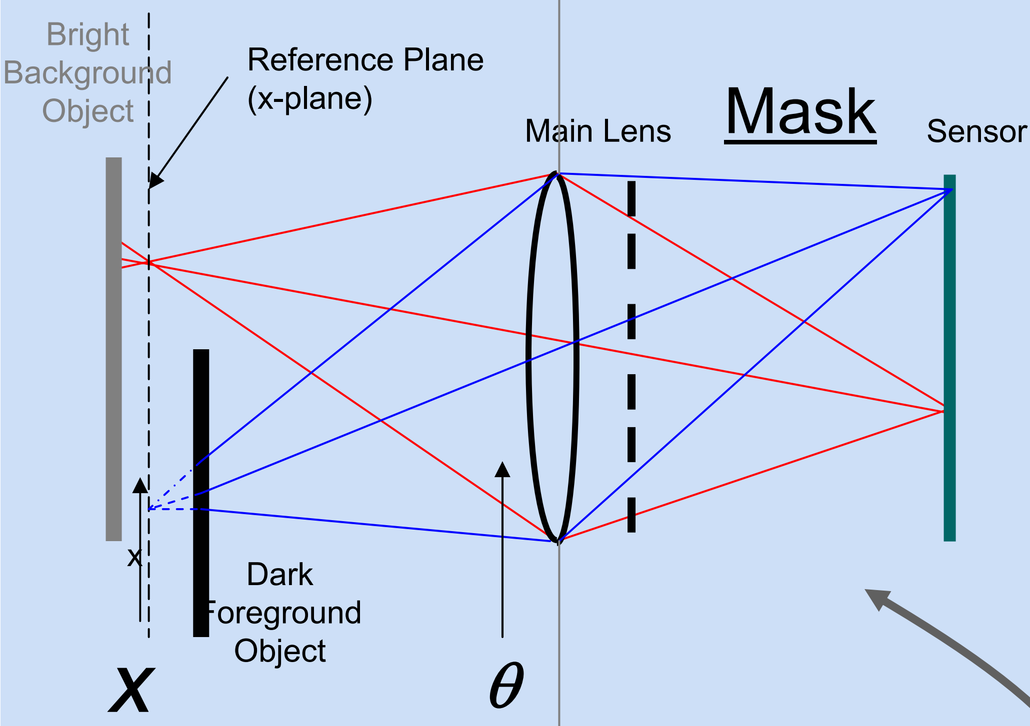

Bright Background Object
Reference Plane (x-plane)
Main Lens
Mask
Sensor
x
Dark Foreground Object
X
θ
Convolution with the Fourier transform of the mask
Fourier Domain Light Field.



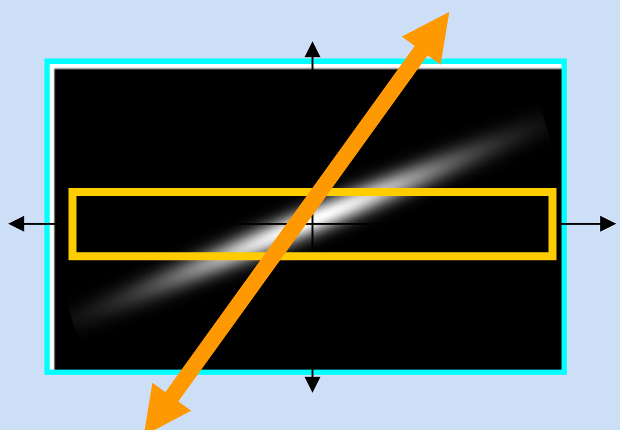
Convolution with the Fourier transform of the mask



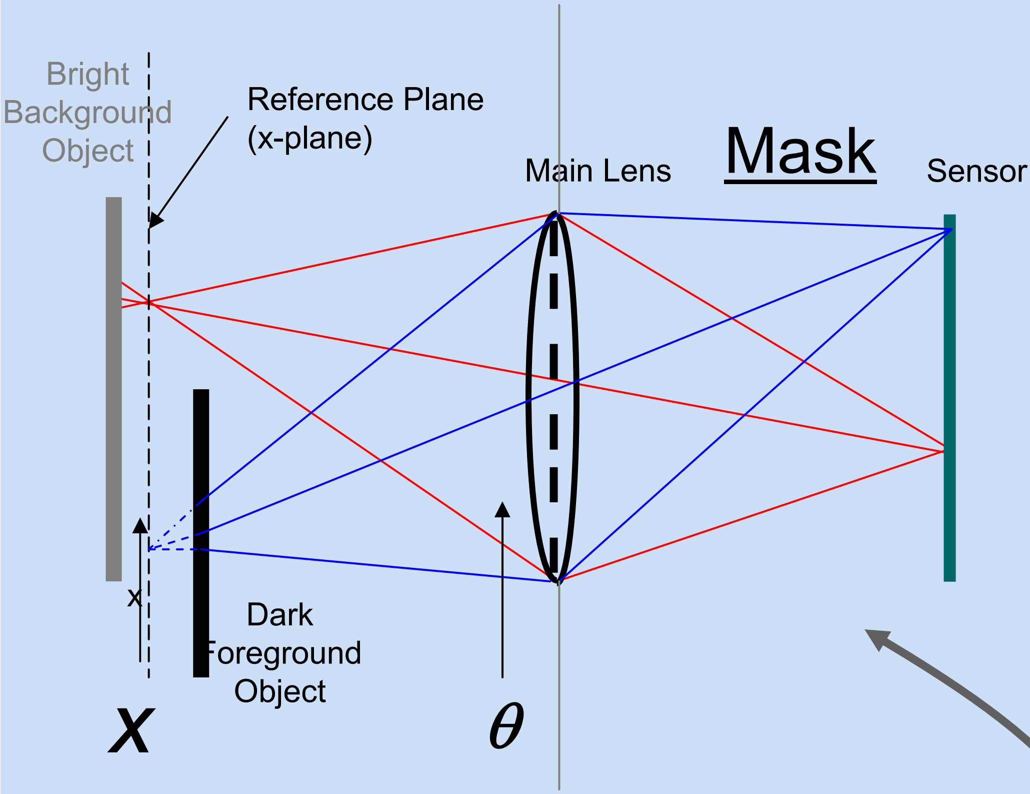
Fourier Domain Light Field.



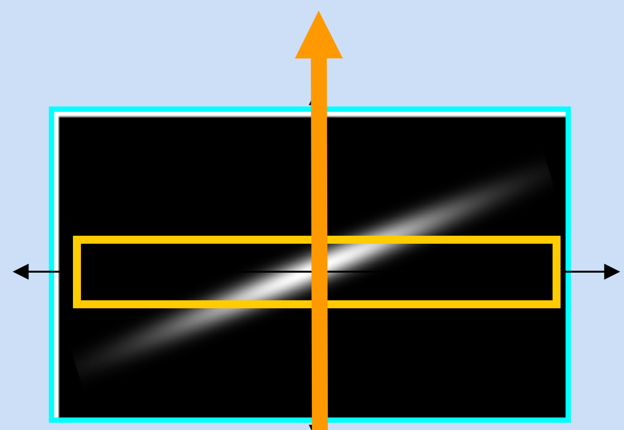
Convolution with the Fourier transform of the mask



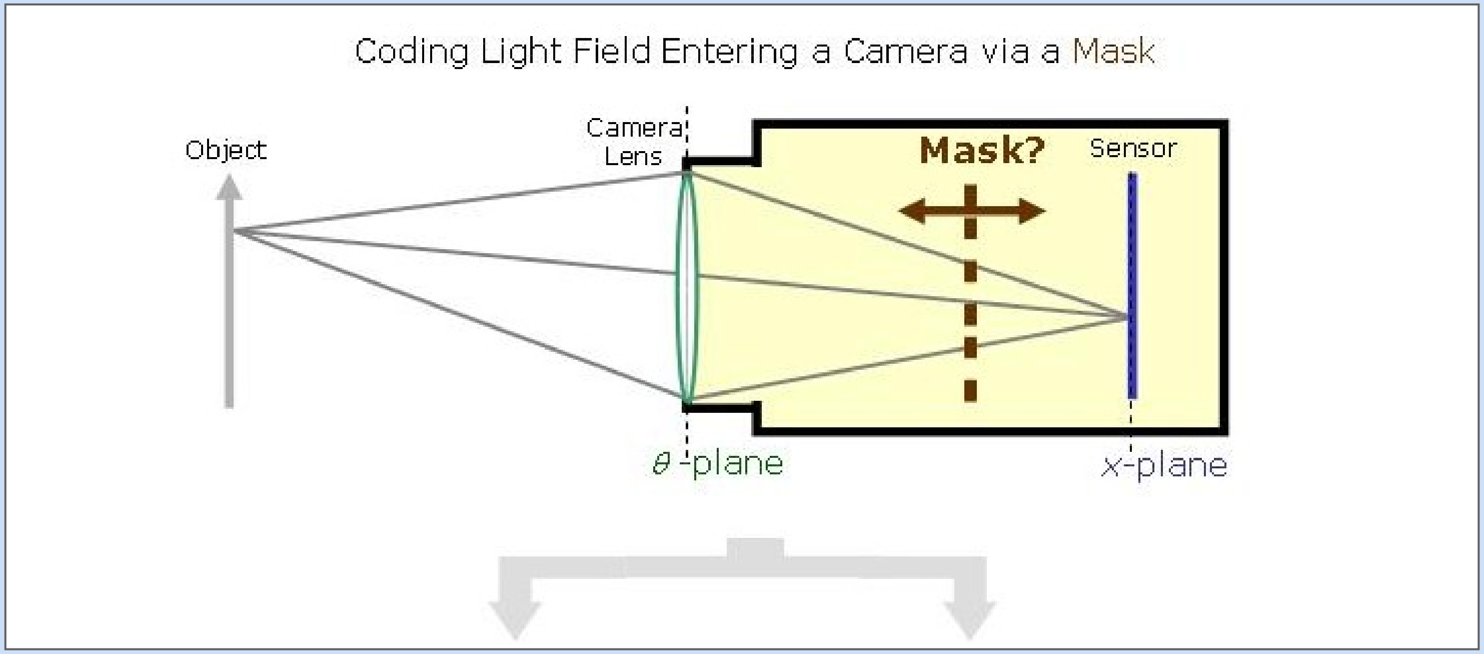
Fourier Domain Light Field.

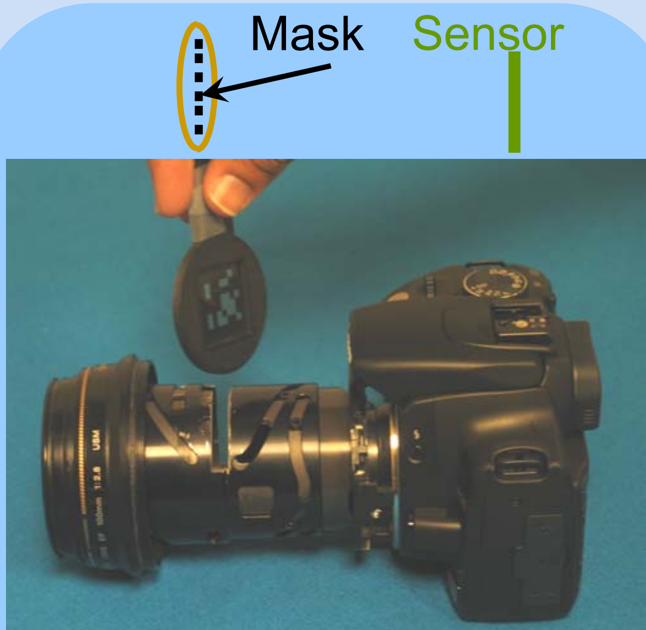


Convolution with the Fourier transform of the mask

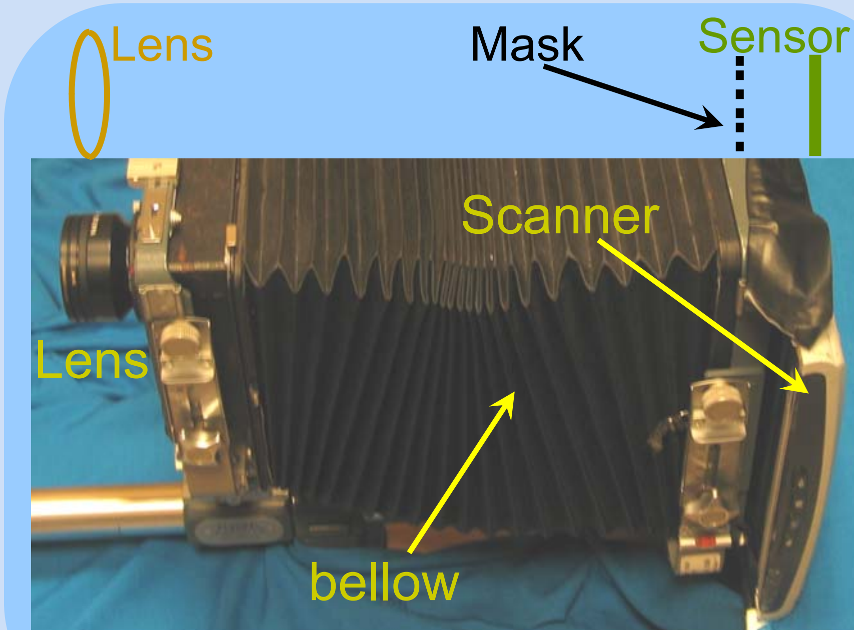


Fourier Domain Light Field.



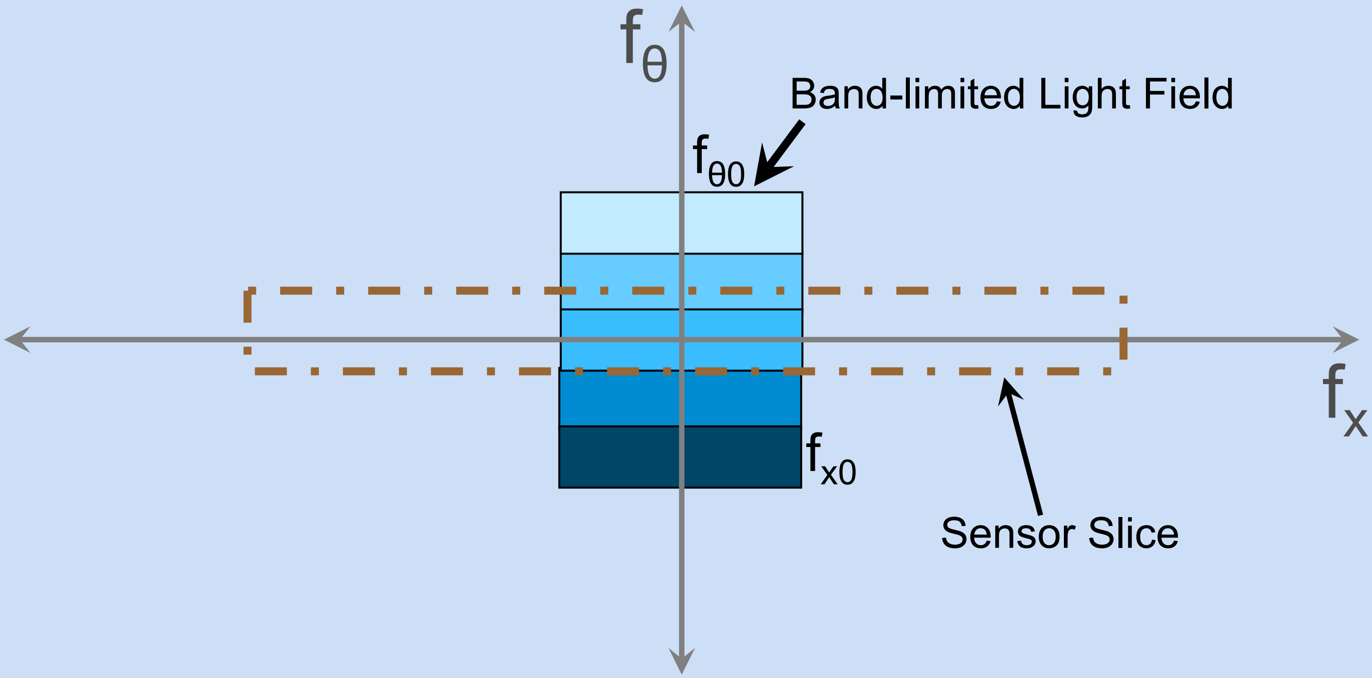


Encoded Blur Camera



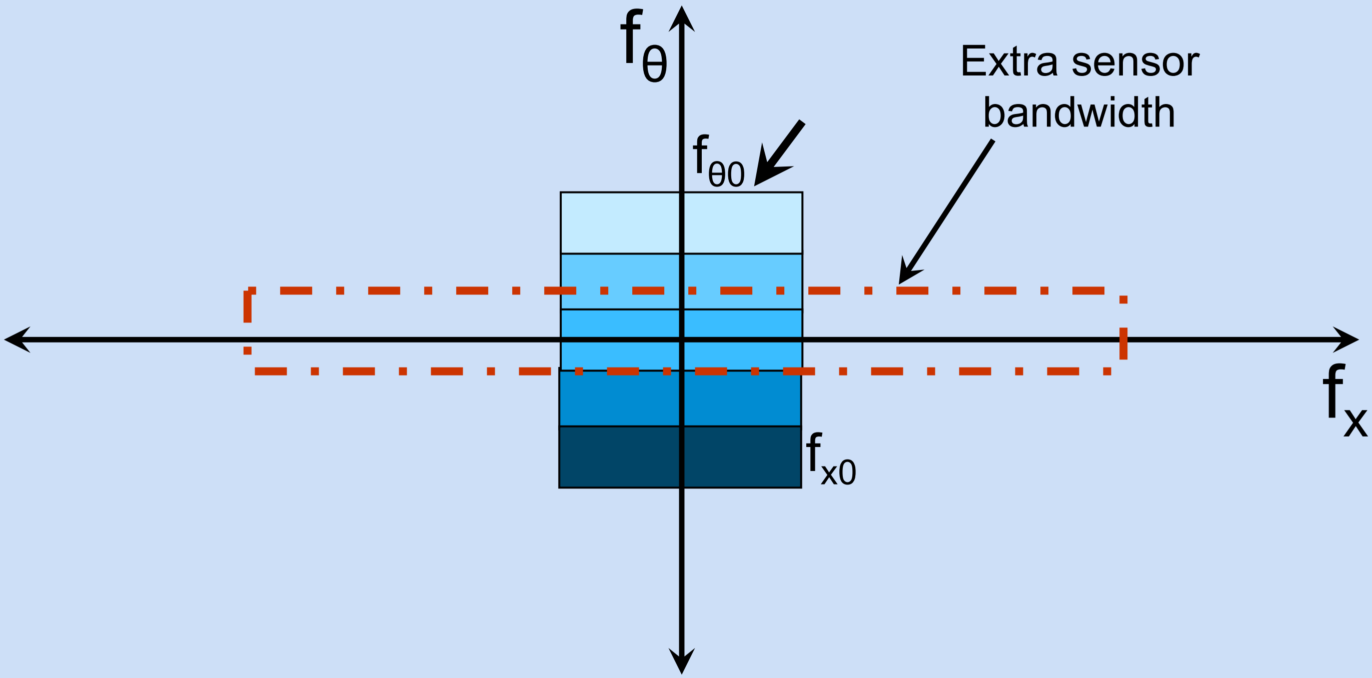
Heterodyne Light Field Camera

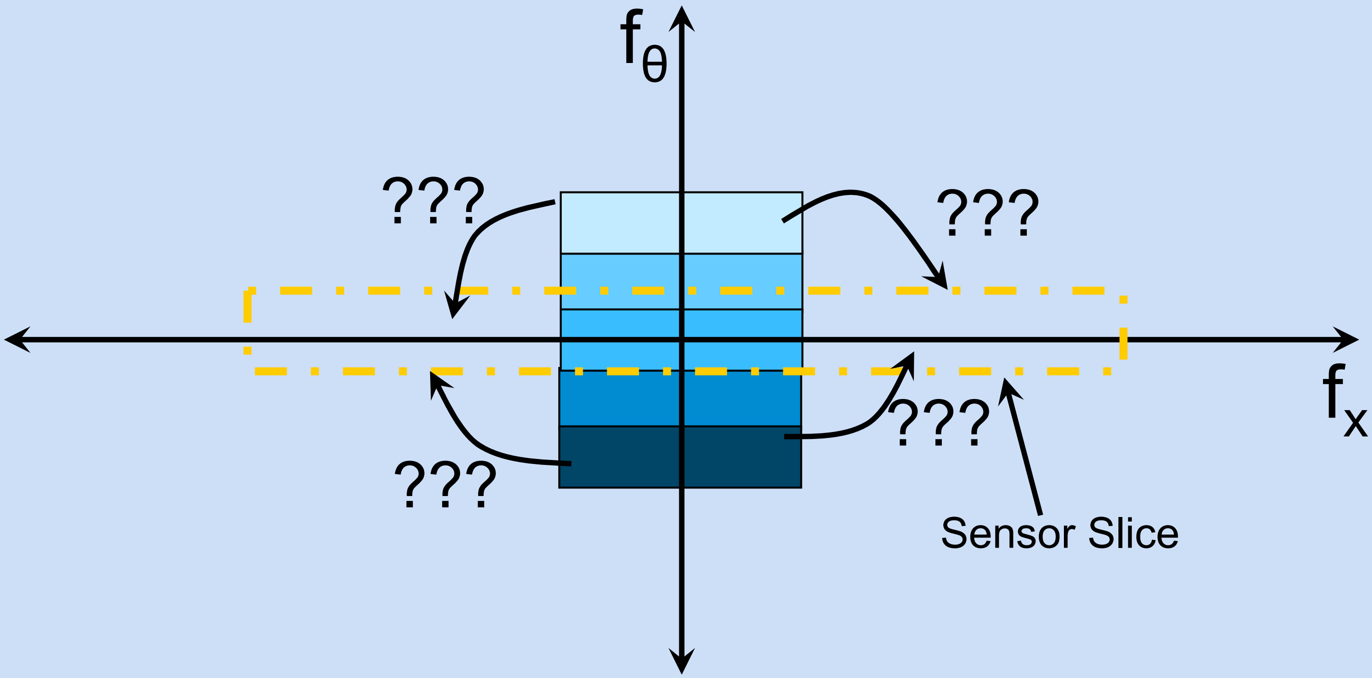
How to Capture 4D Light Field with 2D Sensor ?



Fourier Light Field Space

Extra sensor bandwidth cannot capture extra *dimension* of the light field

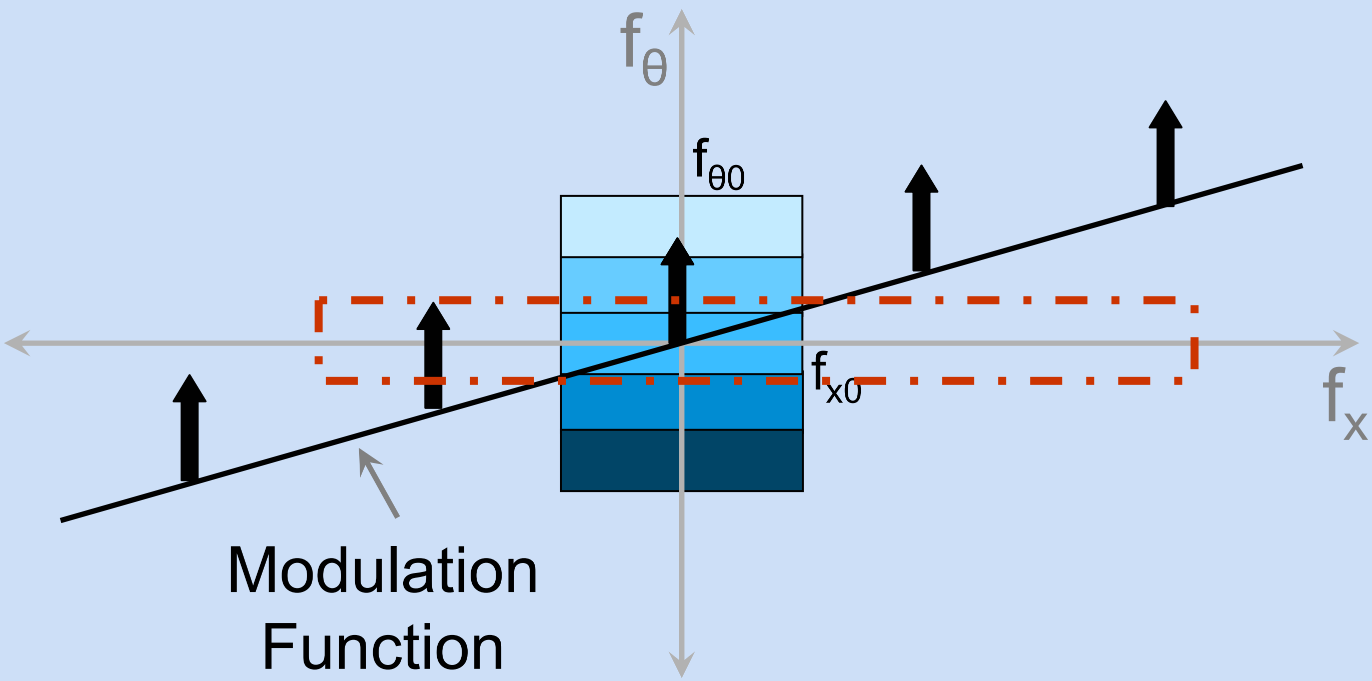




f_θ
???
???
???
???
f_x
Sensor Slice

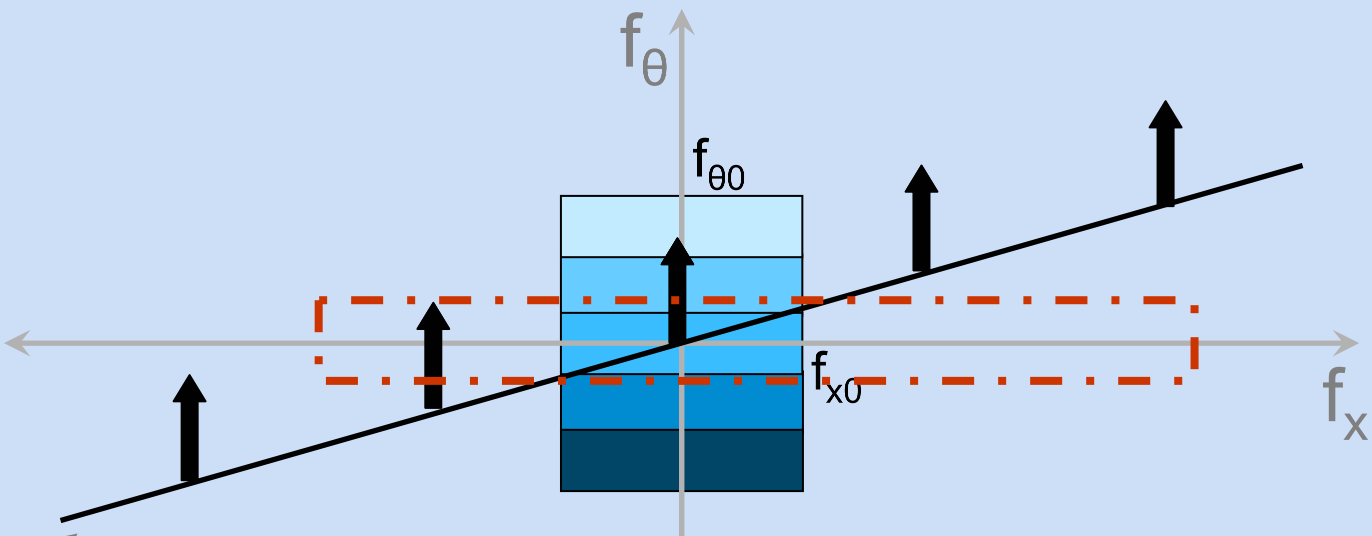
Solution: Modulation Theorem

Make spectral copies of 2D light field

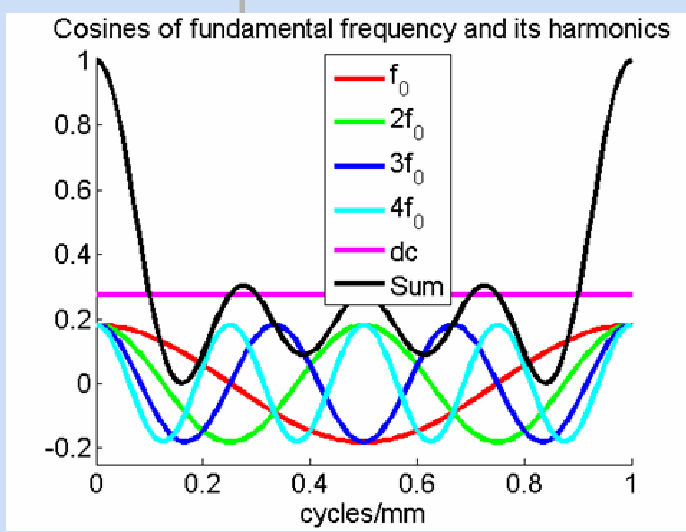


Solution: Modulation Theorem

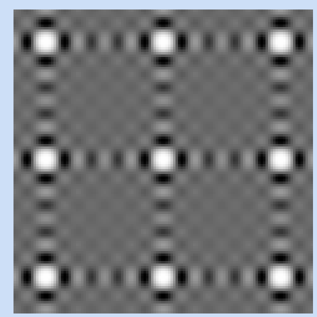
Make spectral copies of 2D light field



Modulation Function
= Sum of Cosines

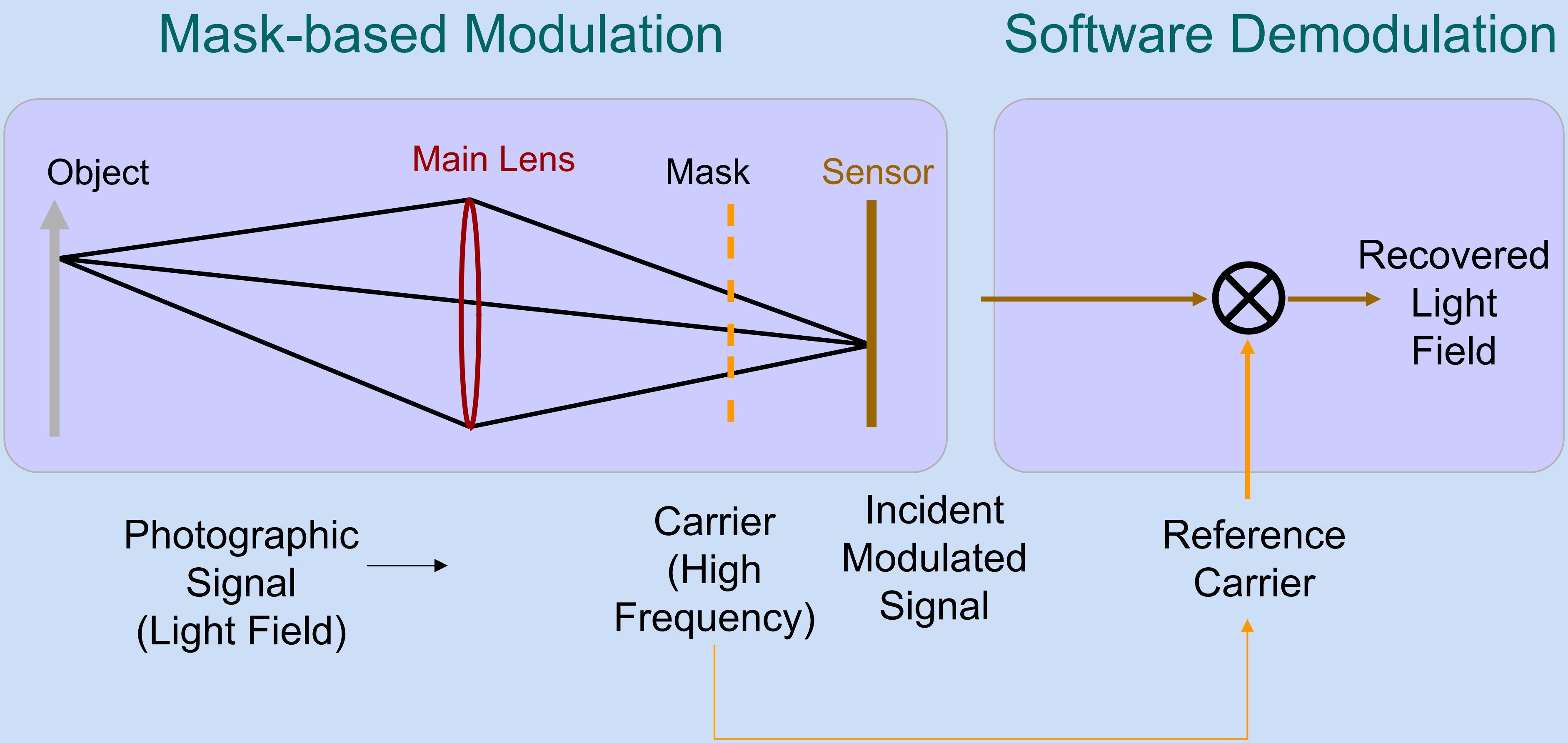


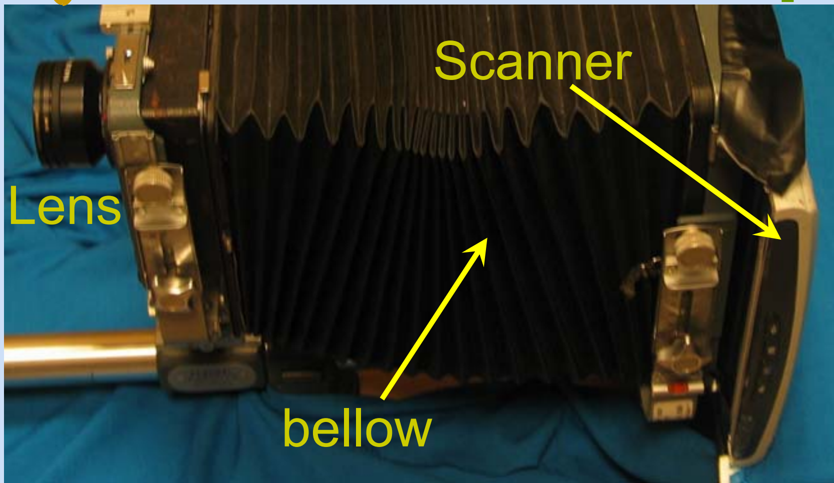
Mask Tile



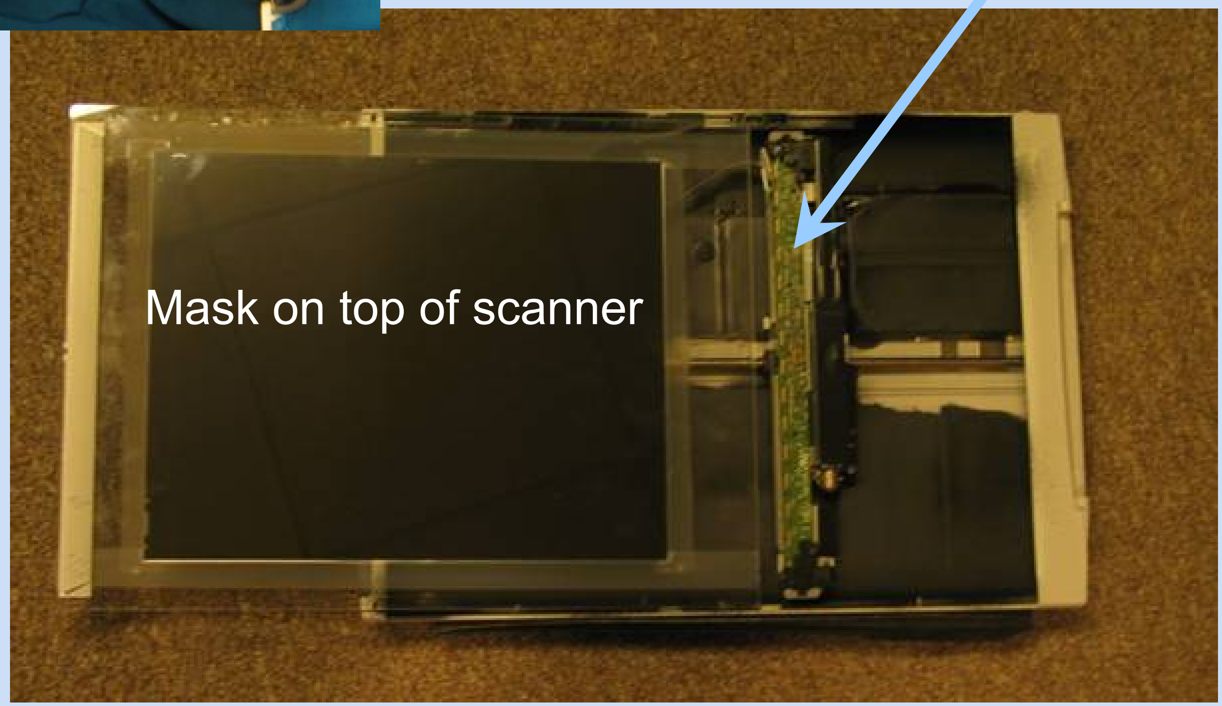
$1/f_0$

How to Capture a 4D Signal with a 2D Sensor ?



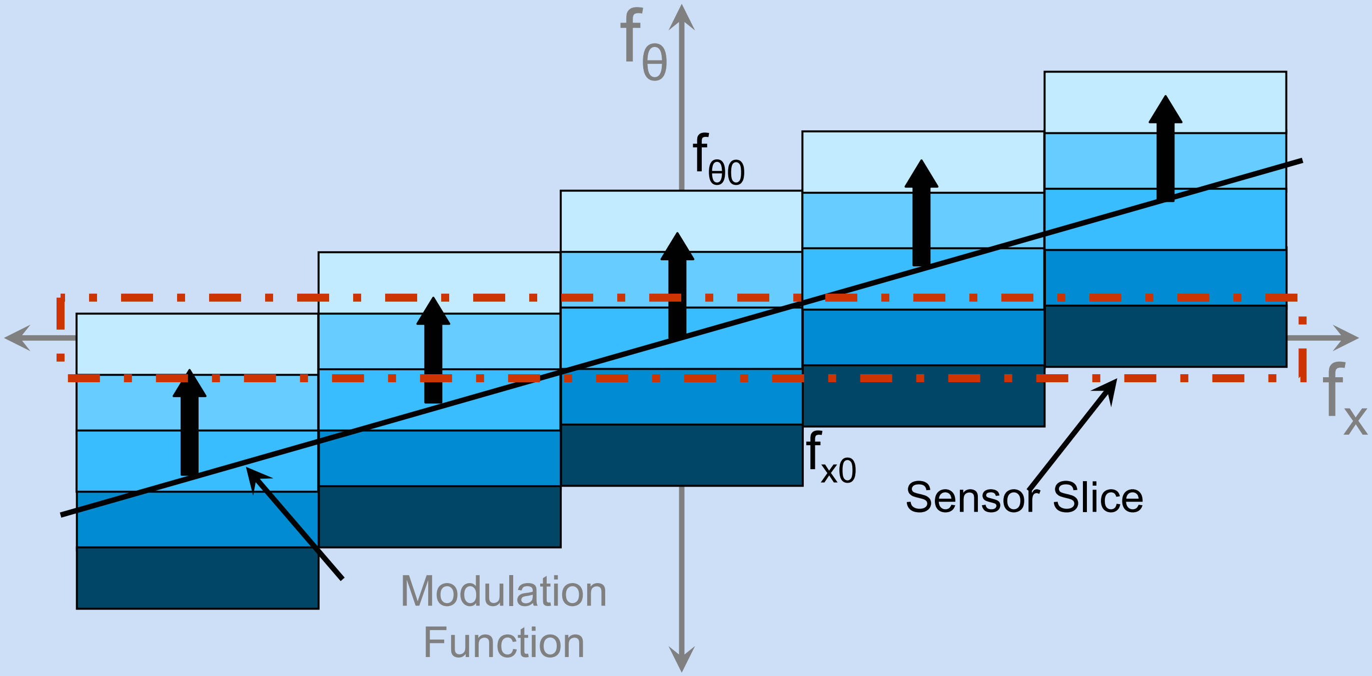


Scanner 1D sensor



Mask = 4 cosines = 9 impulses in Fourier transform
= 9 angular samples

Sensor slice captures entire Light Field



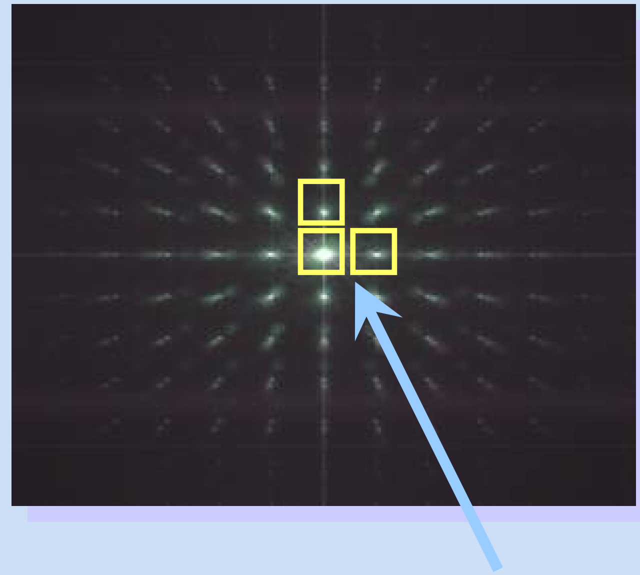
Modulated Light Field

Computing 4D Light Field

2D Sensor image, 1629*2052

2D FFT

2D Fourier Transform, 1629*2052



9*9=81 such tiles

Reshape 2D tiles into 4D planes

181*228*9*9

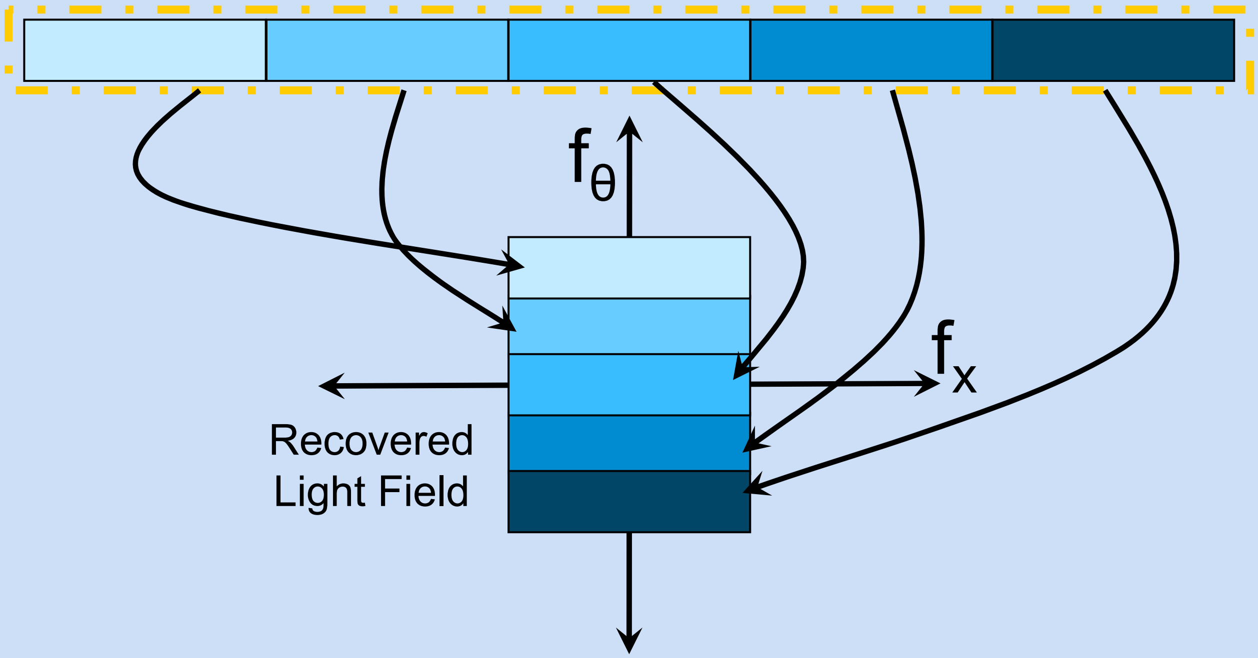
4D IFFT

4D Light Field

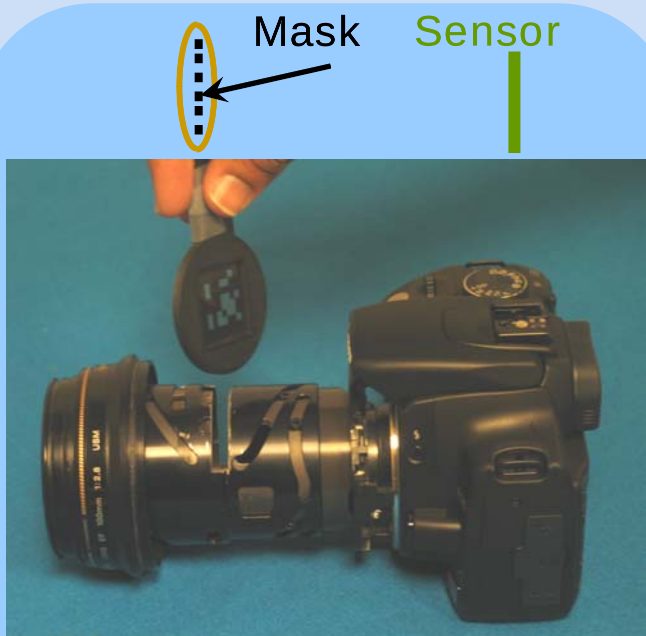
181*228*9*9

To recover light field from sensor slice,

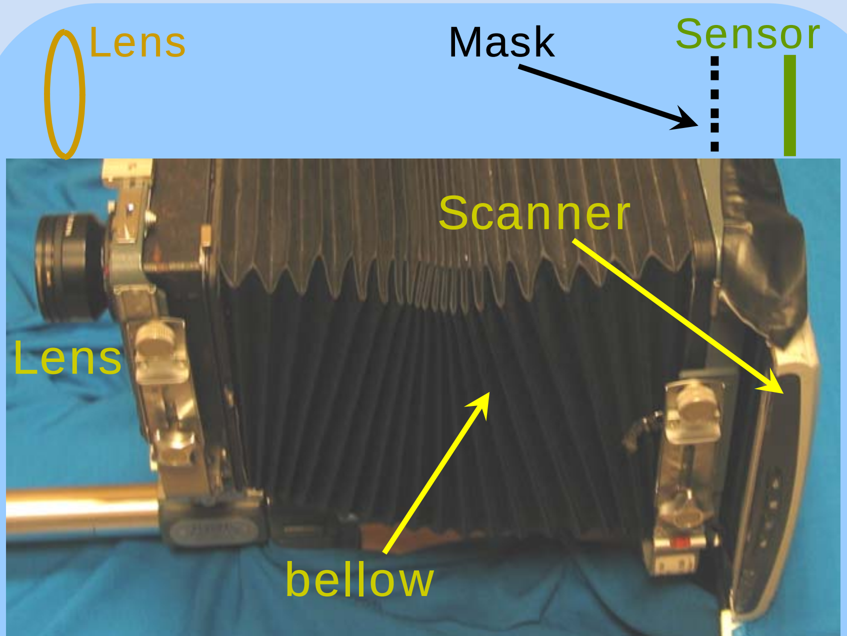
R*eshape* in Fourier tiles



Coded Masks For Cameras



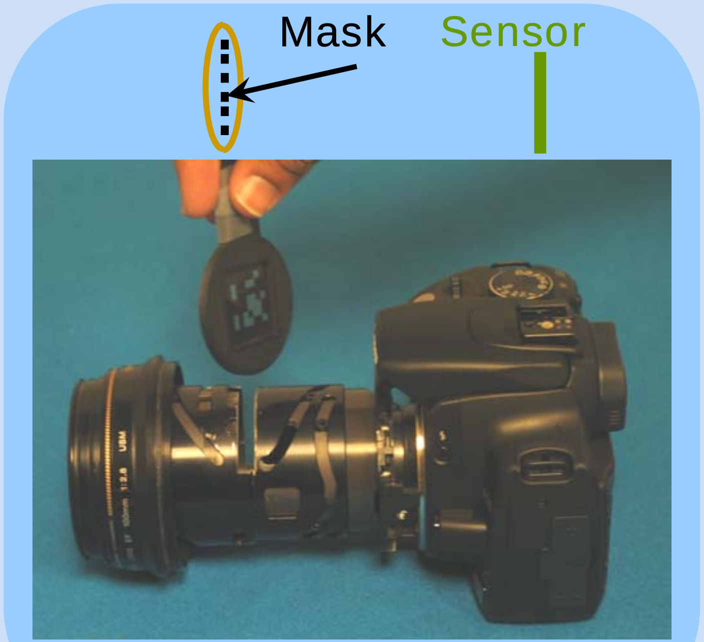
Encoded Blur Camera



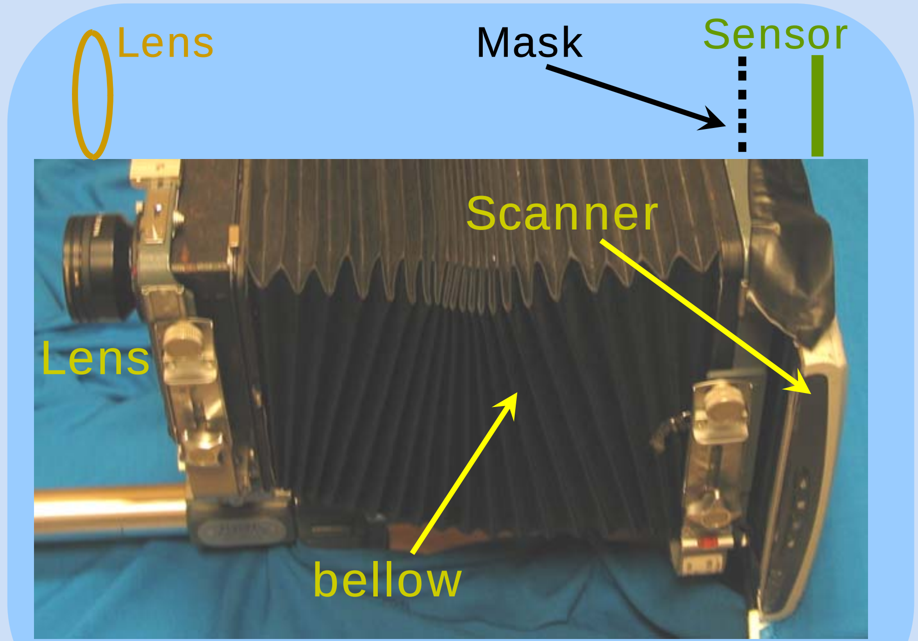
Heterodyne Light Field Camera

- Capture Coded Blur
- Full resolution digital refocussing
- Coarse, **<u>broadband</u>** mask in aperture
- Convolution of sharp image with mask

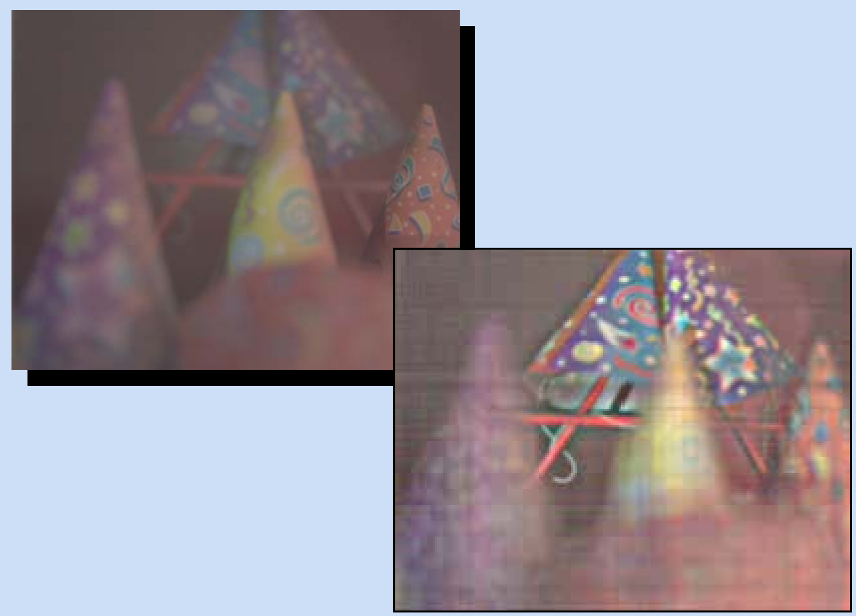
- Capture Light Field
- Complex refocussing at reduced resolution
- Fine, **<u>narrowband</u>** mask close to sensor
- Modulation of incoming light field by mask



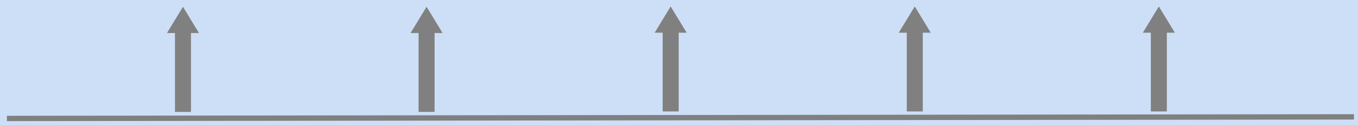
Encoded Blur Camera



Heterodyne Light Field Camera



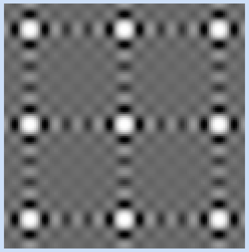
Fourier transform of optimal 1D mask pattern is a set of 1D impulses



Optimal 1D Mask is sum of cosines

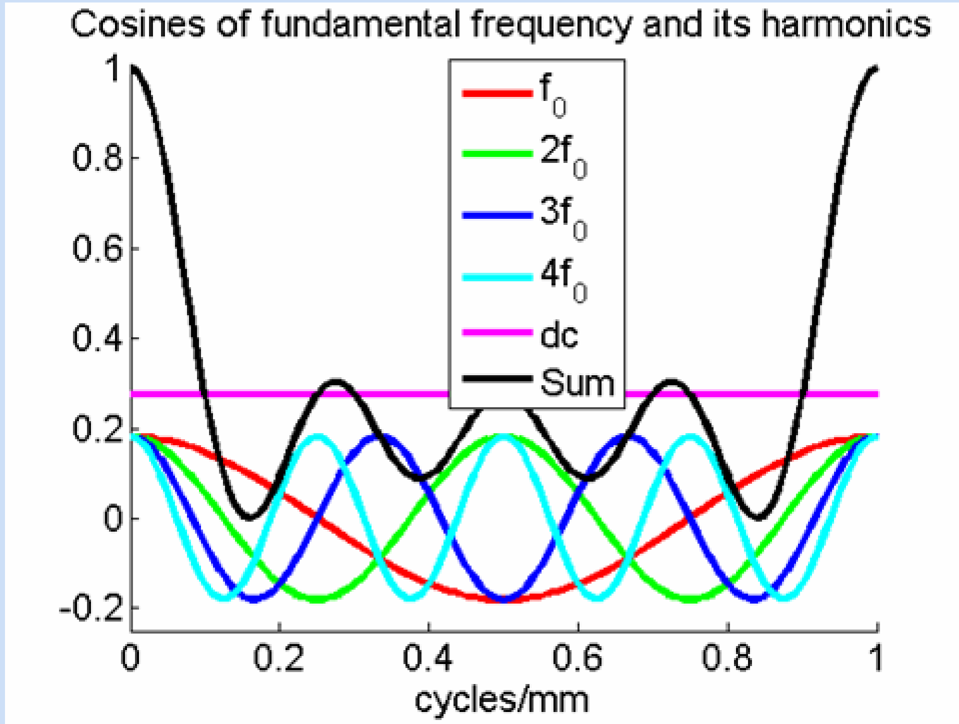
Optimal 2D mask: Sum of cosines in 2D

Number of angular samples = Number of impulses in Fourier transform of the mask along that dimension



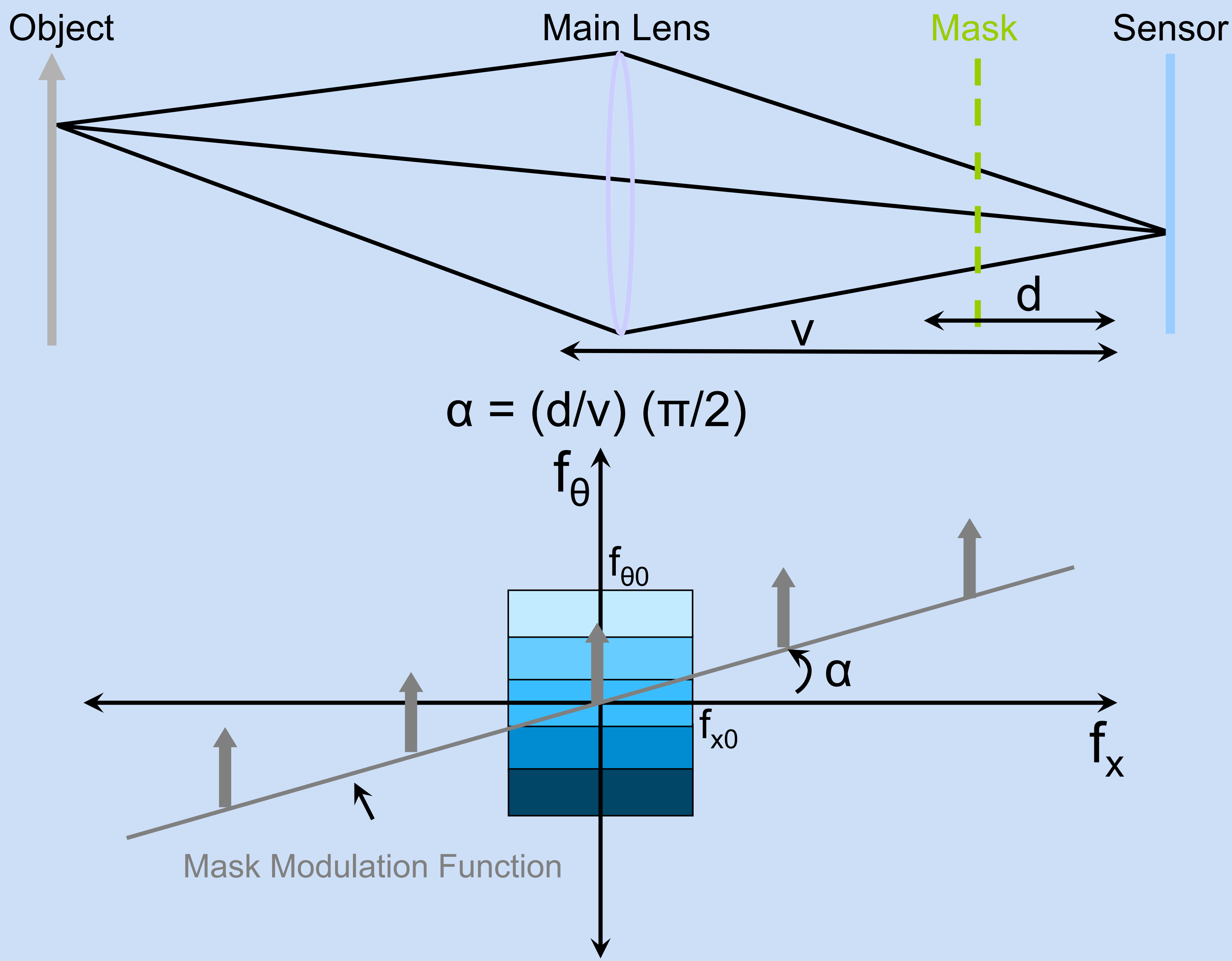
$1/f_0$

Zoom in of the cosine mask

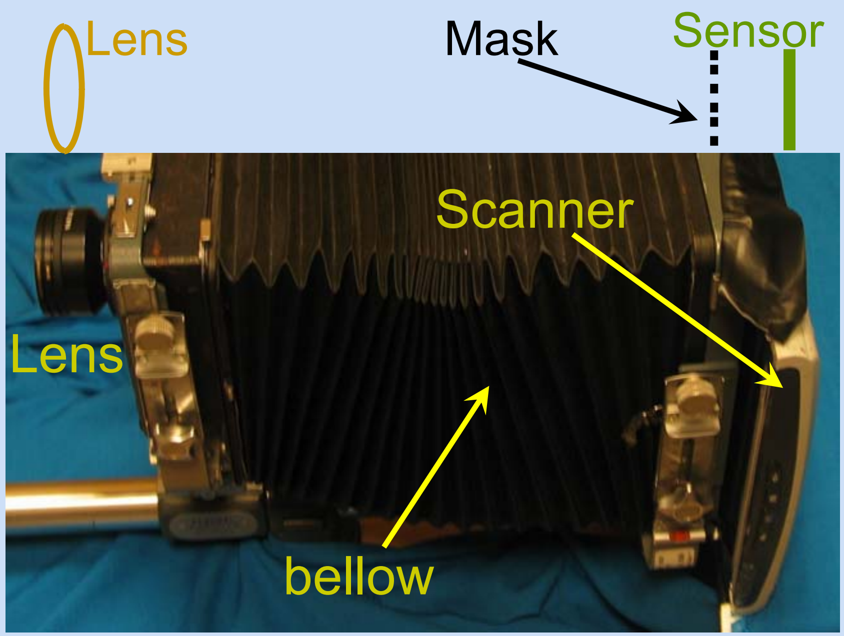


Mask is the sum of cosines with four harmonics. Plot shows the cosines. Since the physical mask cannot have negative values, a constant needs to be added.

Mask-based Heterodyning



Implementation



Light Field Camera

We use Canon flatbed scanner as the sensor and Nikkor lens in front. The mask is placed is about 1 cm in front of the sensor.