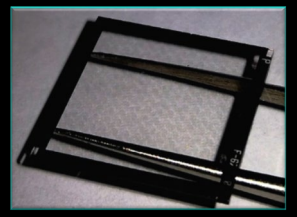
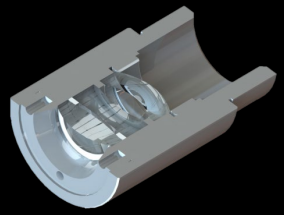





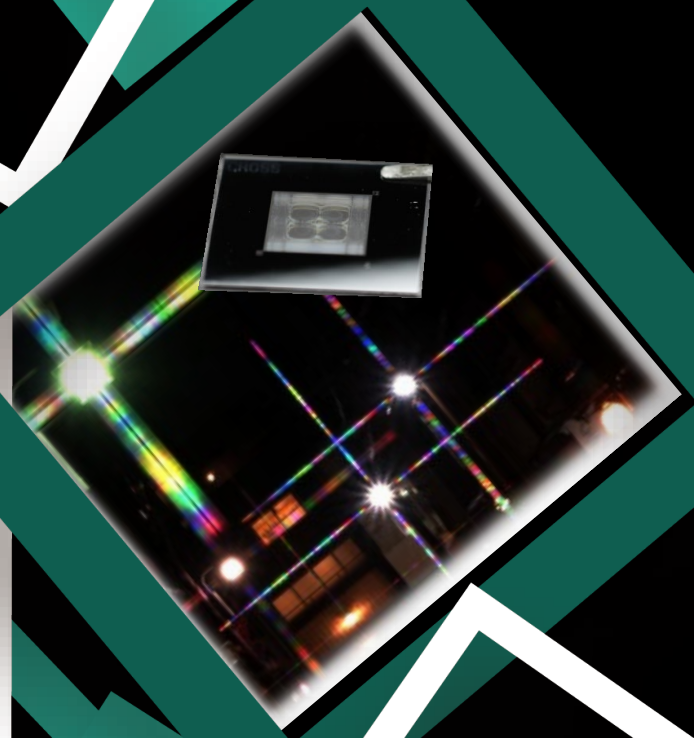

Computational Imaging

Lecture 24: End-to-end Computational Camera Design

点昀 POINT SPREAD

Qilin Sun（孙启霖）

香港中文大学（深圳）

点昀技术（Point Spread Technology）

香港中文大學(深圳)
The Chinese University of Hong Kong, Shenzhen

- Step One: Joint Optimization of Optics and Image Recovery
  - Learned Large Field-of-View Imaging with Thin-Plate Optics
- Step Two: Compressive and Optically Coded Super-resolution SPAD Camera
  - Compressive and Optically Coded Super-resolution SPAD Camera
- Step Three: Enabling Comprimization for Color Channels
  - Learning Rank-1 Diffractive Optics for Single-shot High Dynamic Range Imaging
- Step Four: End-to-end Complex Lens Design
  - End-to-end Complex Lens Design with Differentiable Ray-Tracing

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Step One: Joint Optimization of Optics and Image Recovery

Learned Large Field-of-View Imaging with Thin-Plate Optics

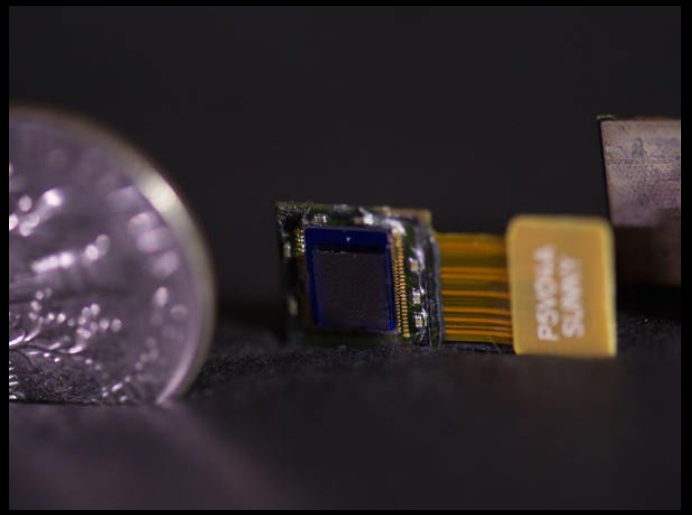
Thin-Plate Optics

- Diffractive optics
- Metasurfaces

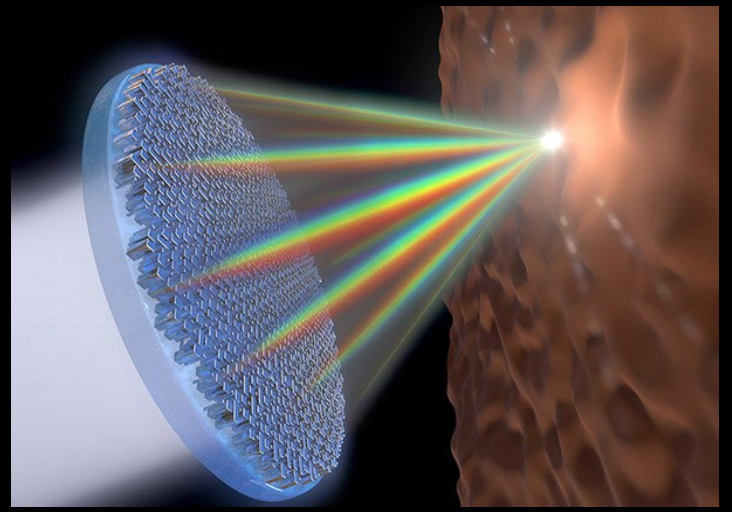
- Thin form factor
- Large design freedom

- Limited field-of-view
- Limited color fidelity
- Limited lens size

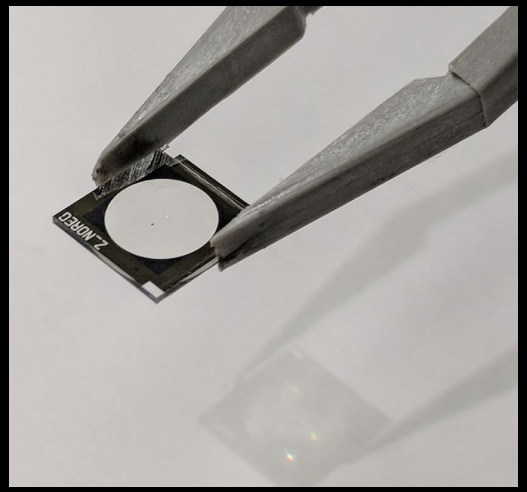
This work



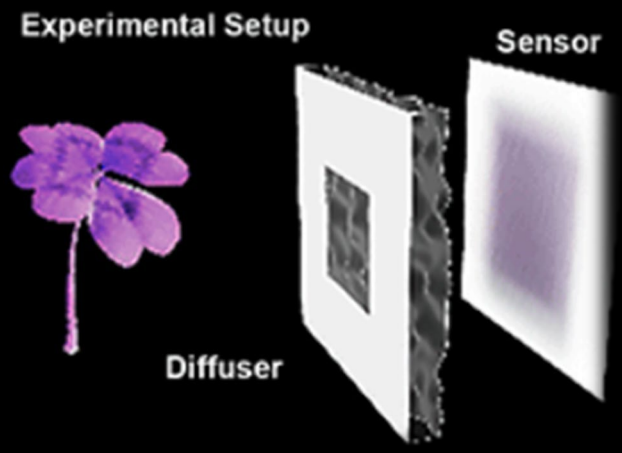
[Ayremlou et al. 2016]



[Capasso et al. 2017]



[Peng et al. 2016]
[Sitzmann et al. 2018]



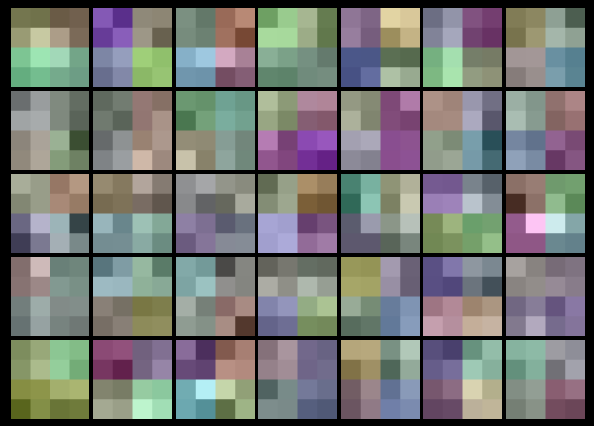
[Antipa et al. 2018]

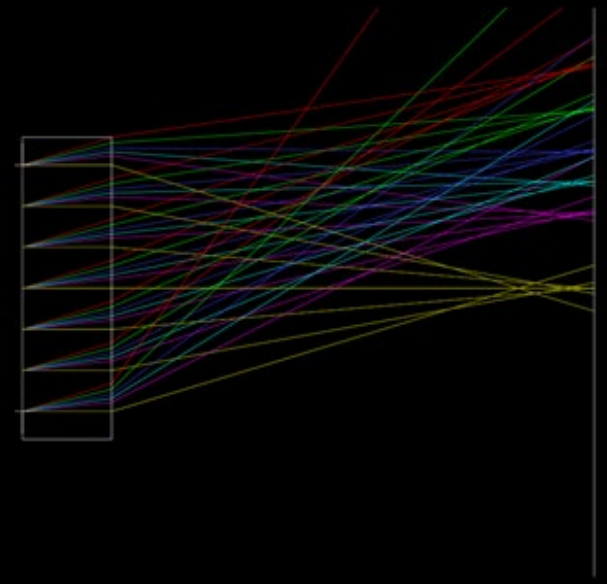
Wide Field-of-View Imaging

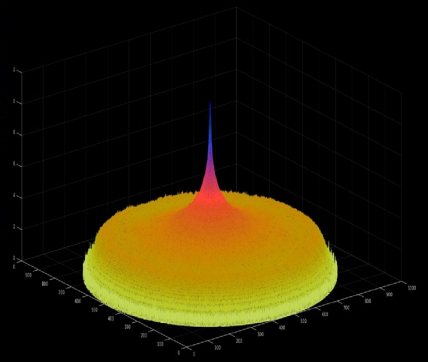
[Peng et al. 2016]
[Heide et al. 2016]
[Ayremlou et al. 2016]
[Sitzmann et al. 2018]

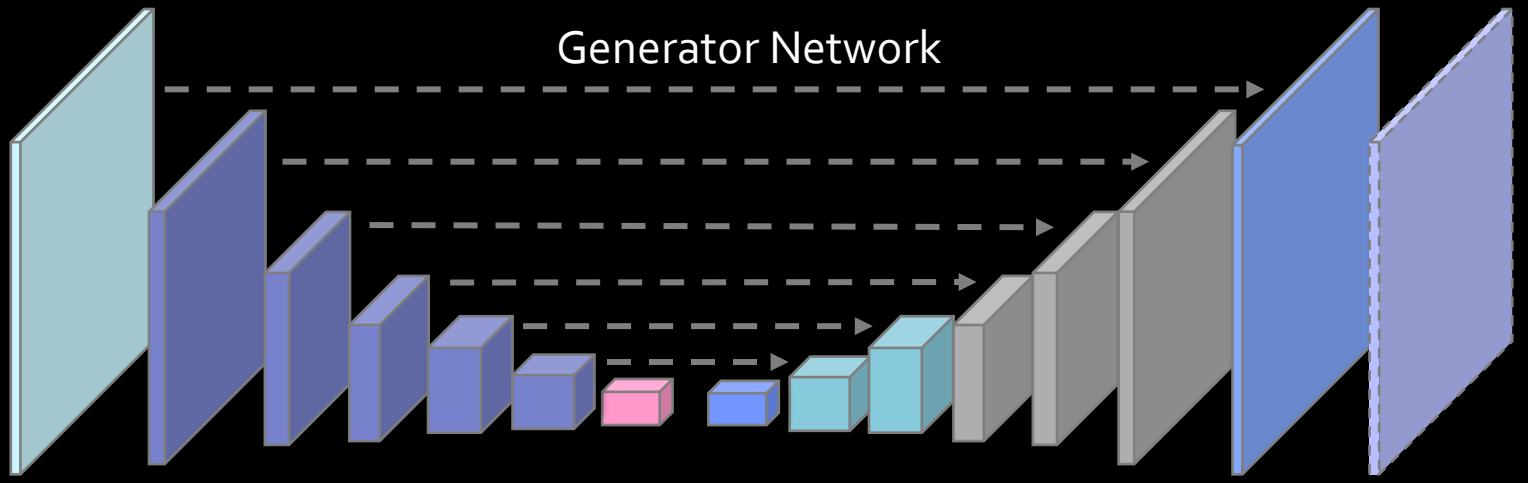
Co-design of Optics and Learned Recovery

Co-design of Optics and Learned Recovery

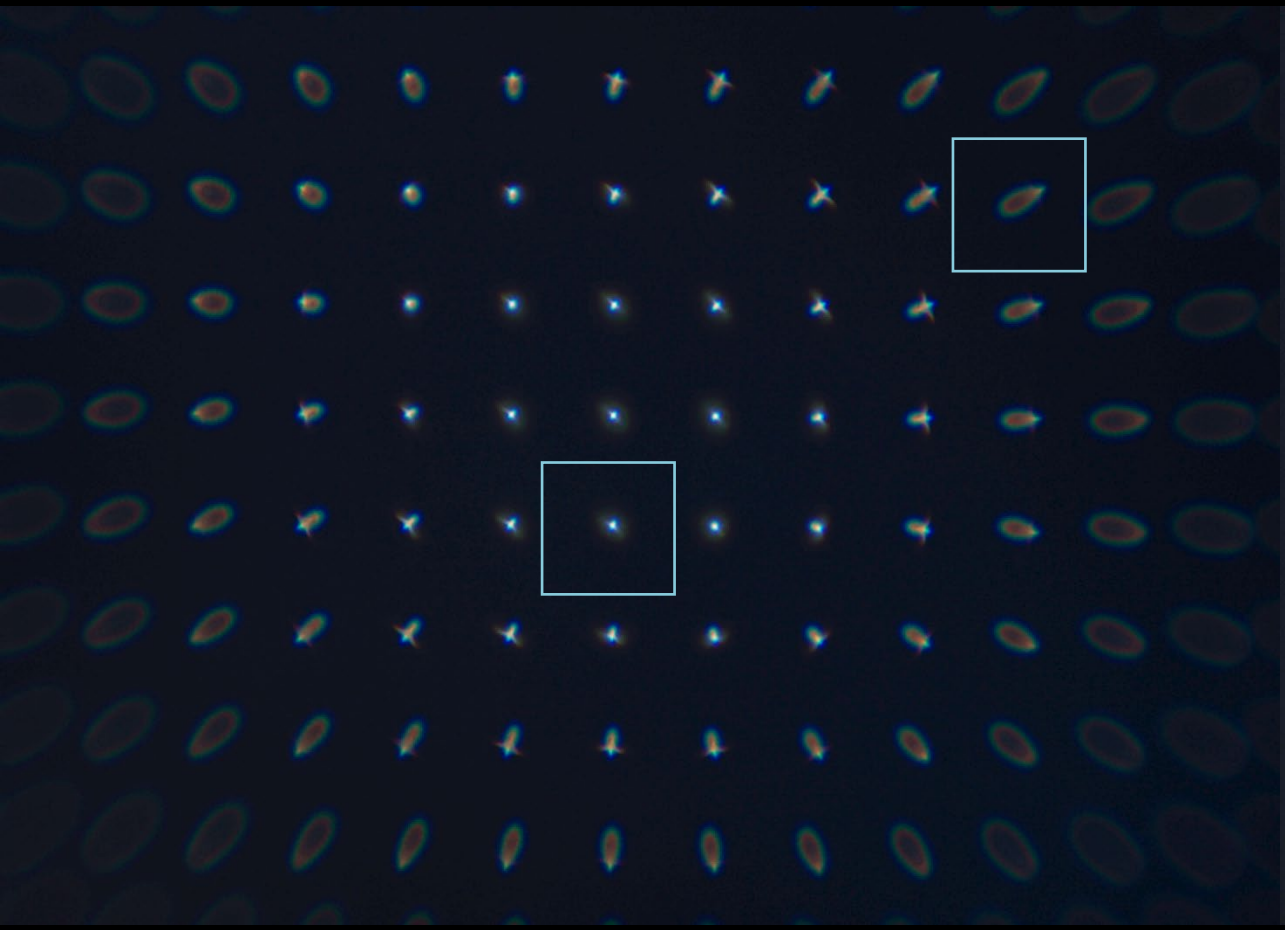


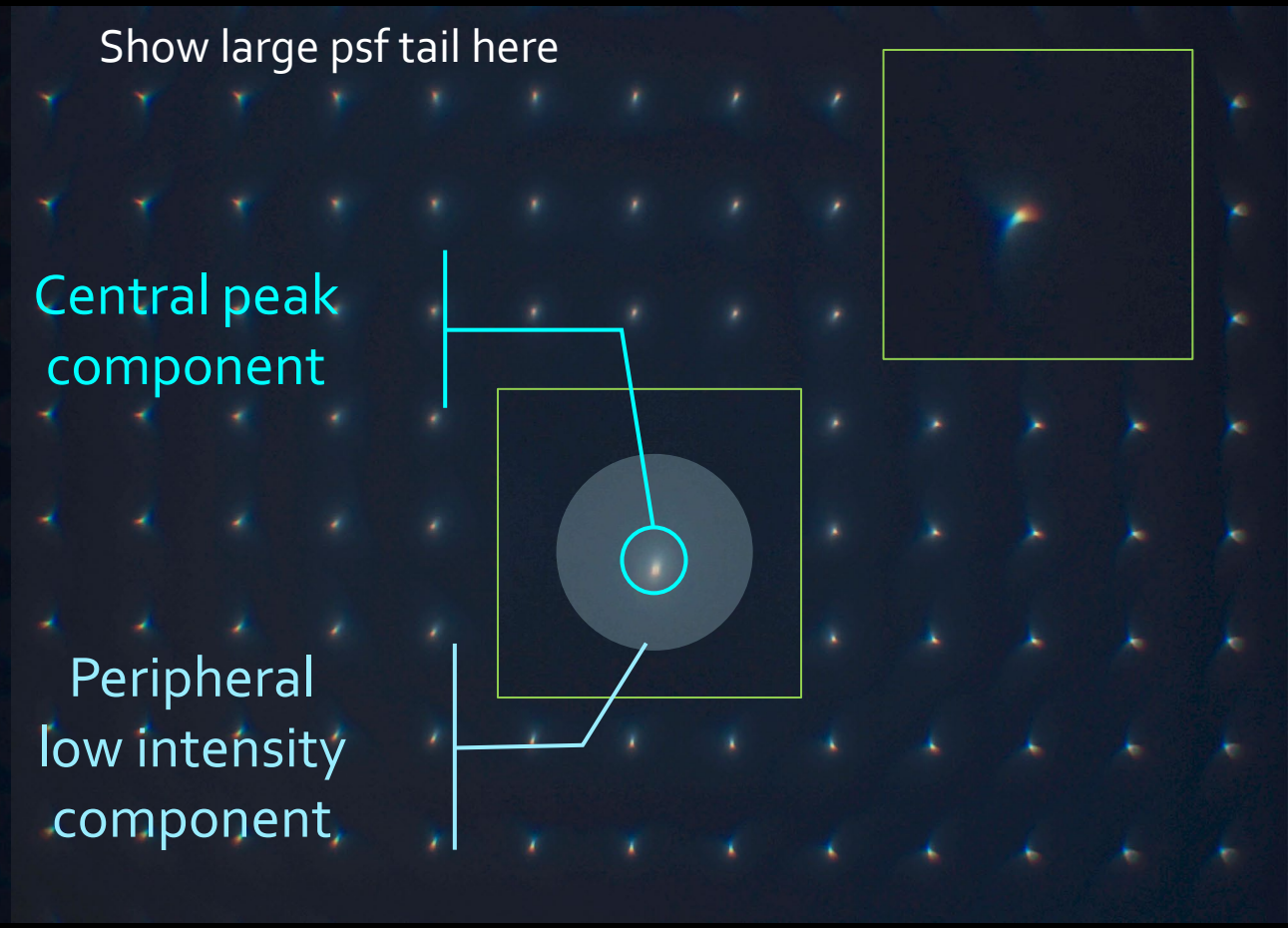






Angularly-Invariant PSF

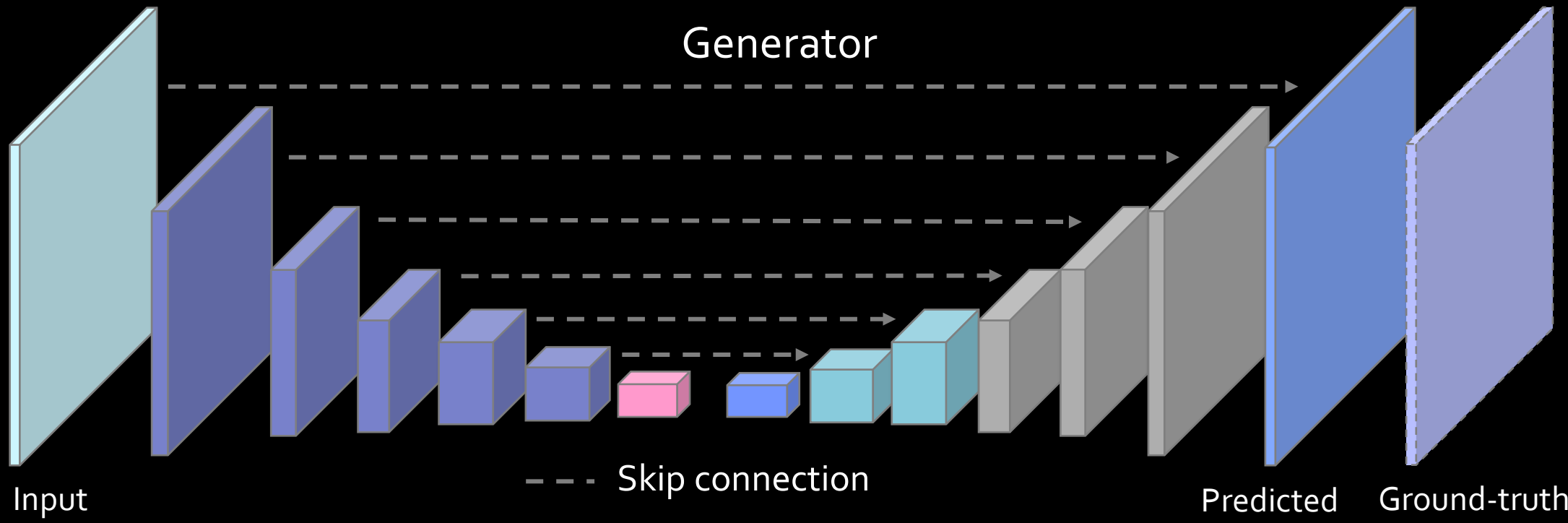


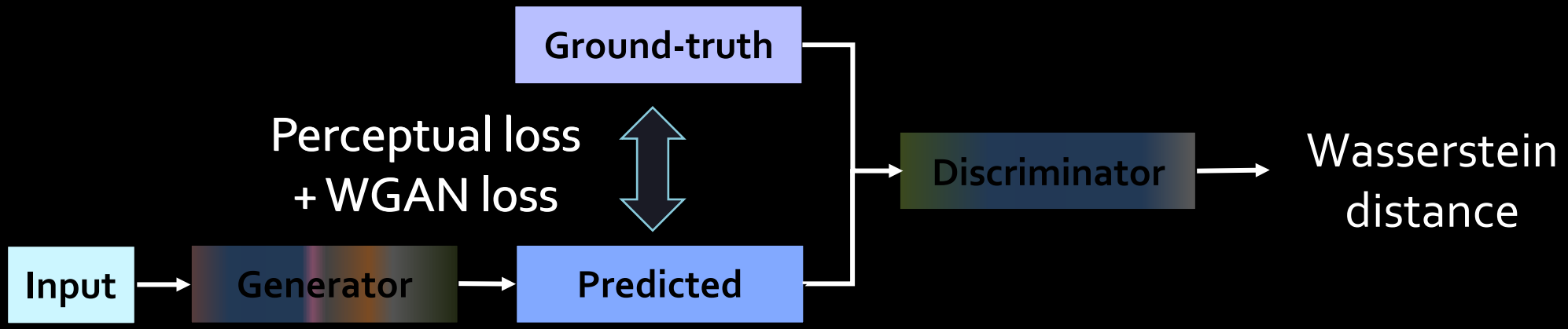


Aspherical lens (f = 50 mm)

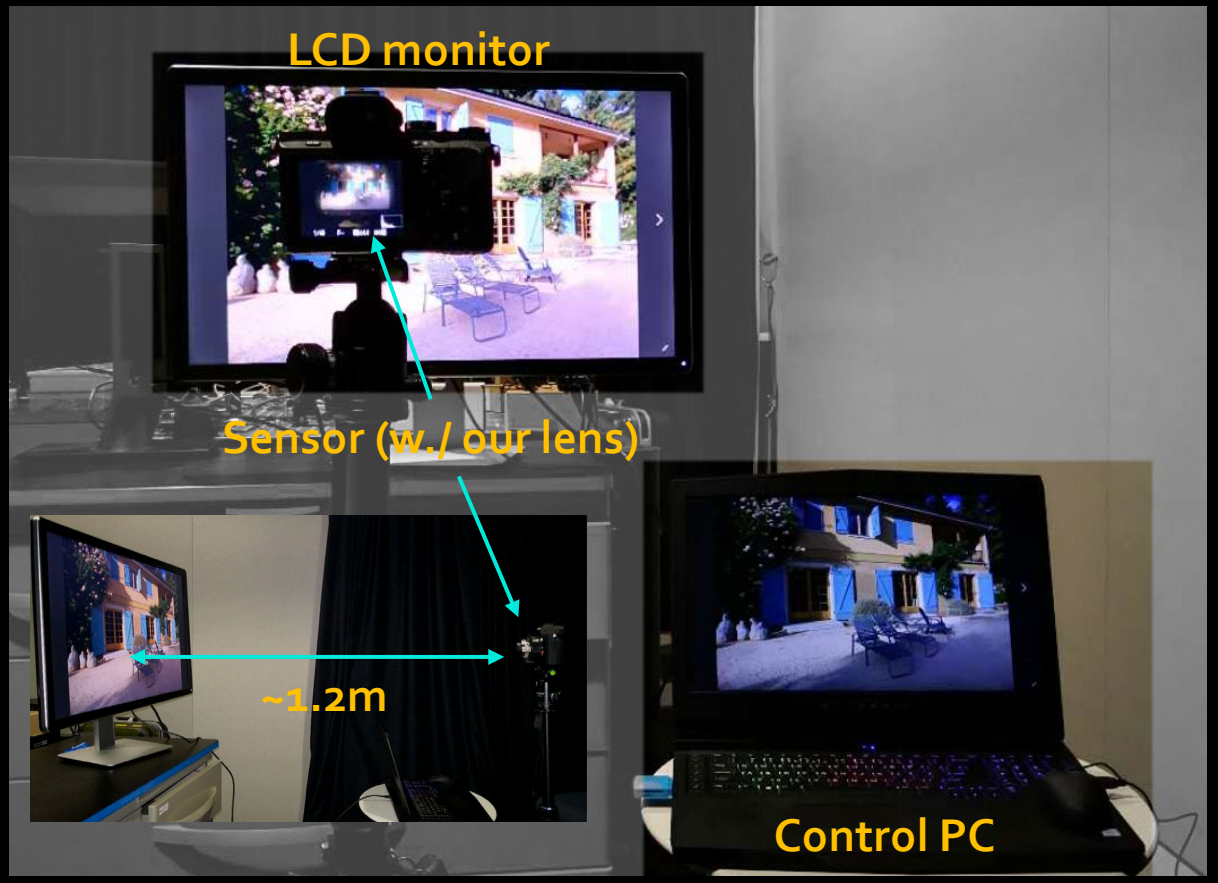
Our design lens (f = 43 mm)

Learned Reconstruction Framework



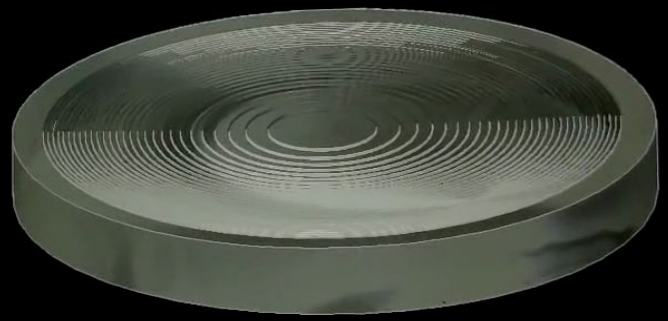


Automated Training Data Acquisition

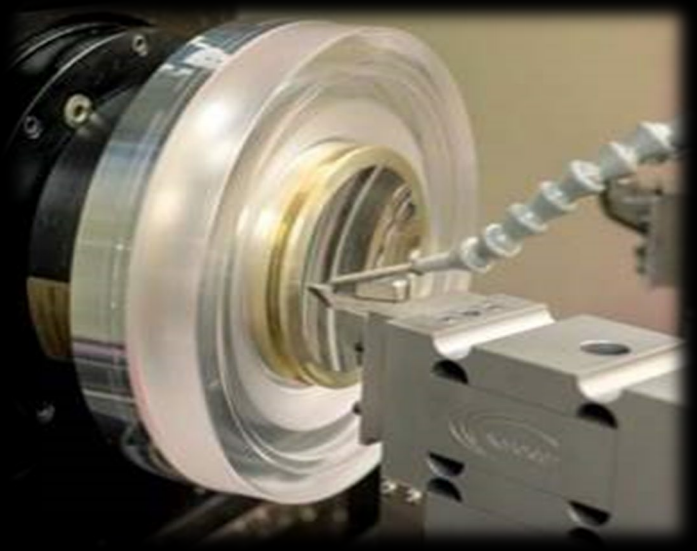


814 image pairs in total

Prototypes



- Clear aperture D : 23.4 mm
- Focal length f : 43.0 mm
- Field of view : 50+ deg.



10 mm substrate　　3 mm substrate

Remarks

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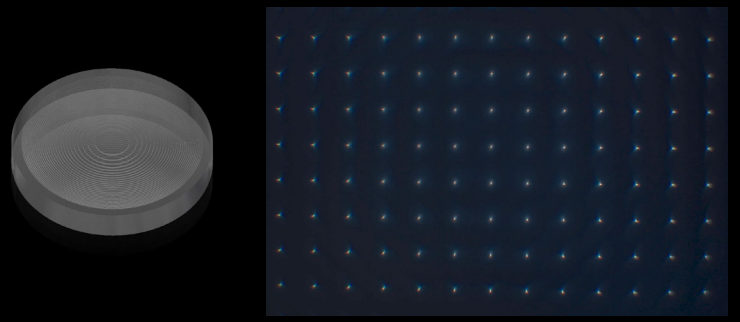
- Large field-of-view + Single element



- Display-capture lab training

- High-quality color imaging

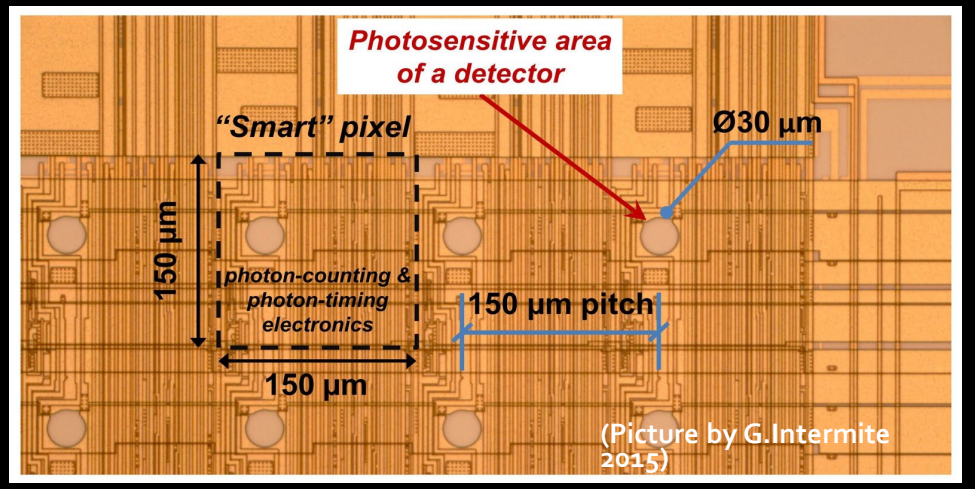
Step Two: The First End-to-end Optics for Single Wavelength

Compressive and Optically Coded Super-resolution SPAD Camera

Motivation

SPAD array sensor

(Picture from MPD)



Low fill-factor and LR image

=

Sampling HR image with low ratio

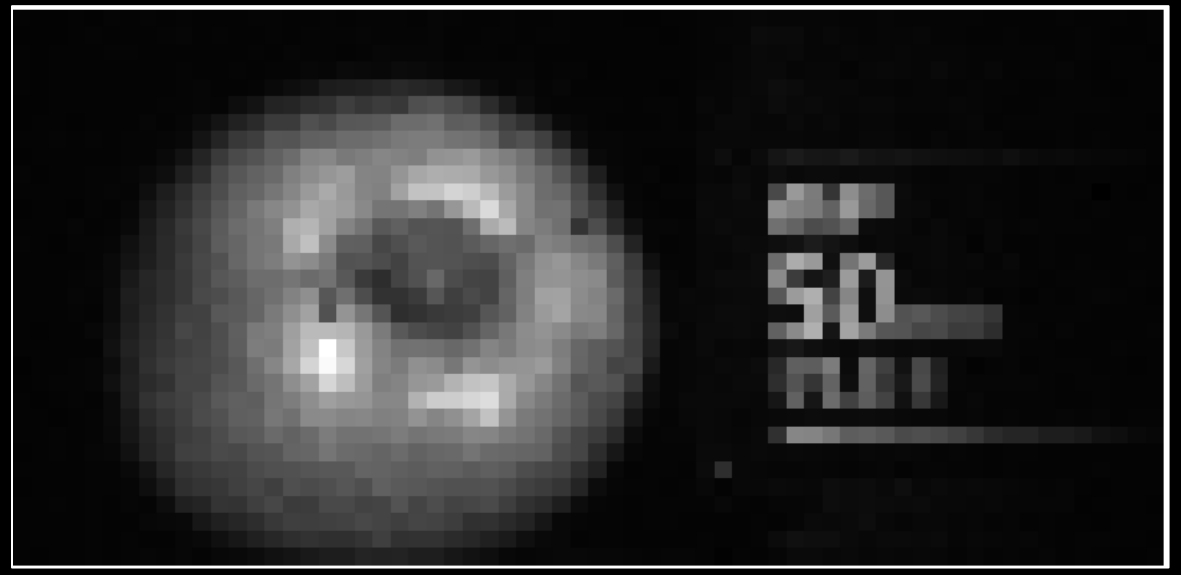
- Single photon level sensitivity
- Pico-second level time resolution
- Low spatial resolution
- Low fill-factor

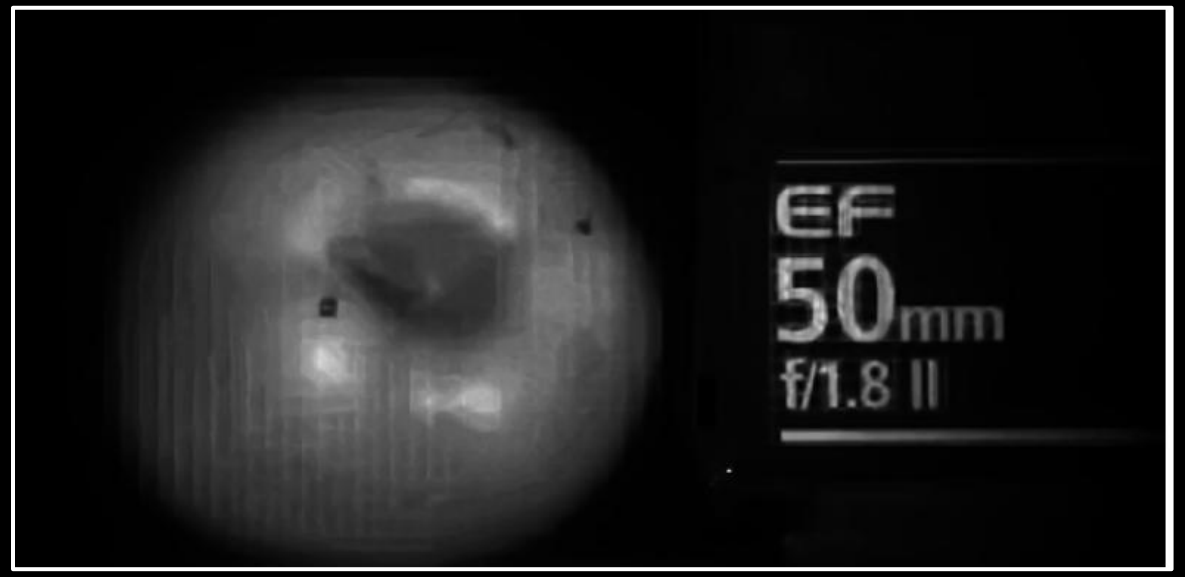
Optimal optics PSF encoding

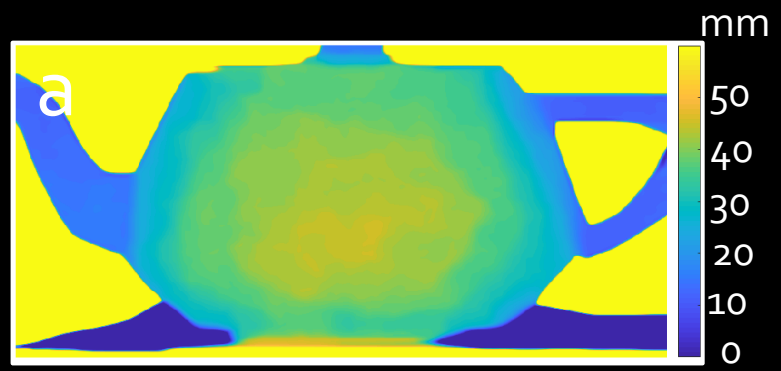
Deep Network based SR method

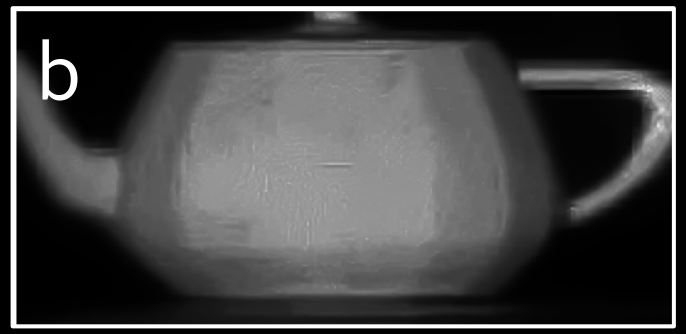
⊕ → Recover HR image with single-shot

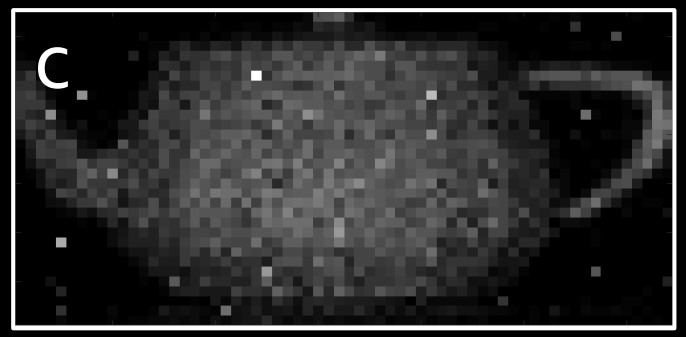
Compressive SPAD Camera—Results



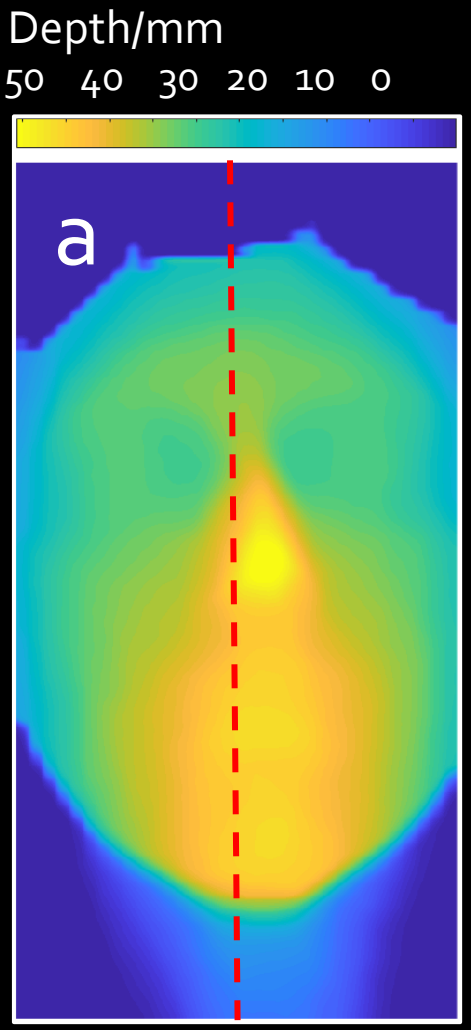


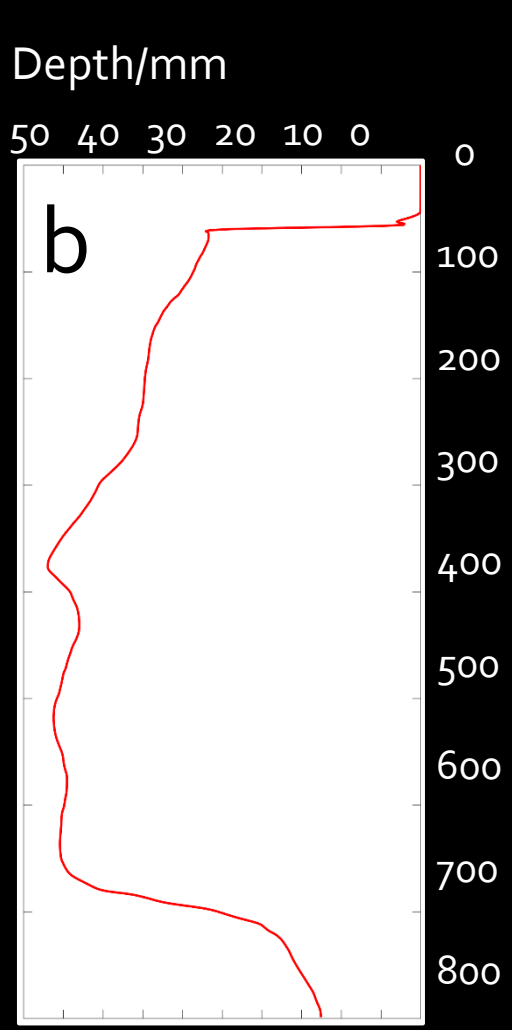


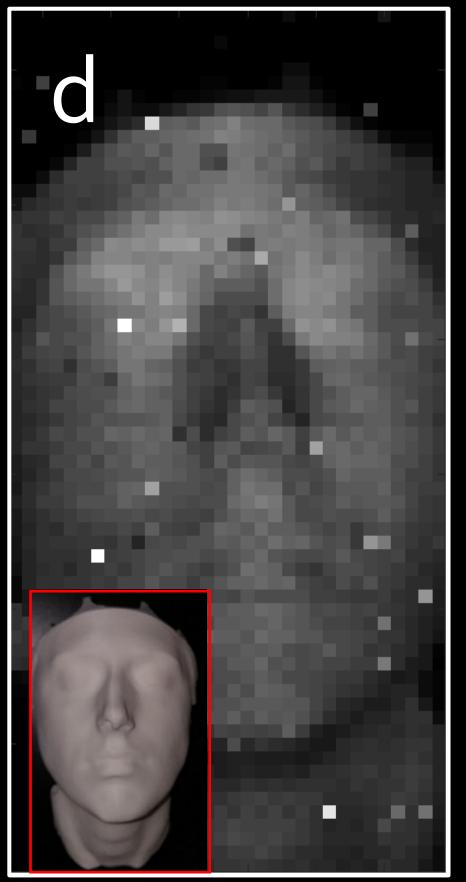




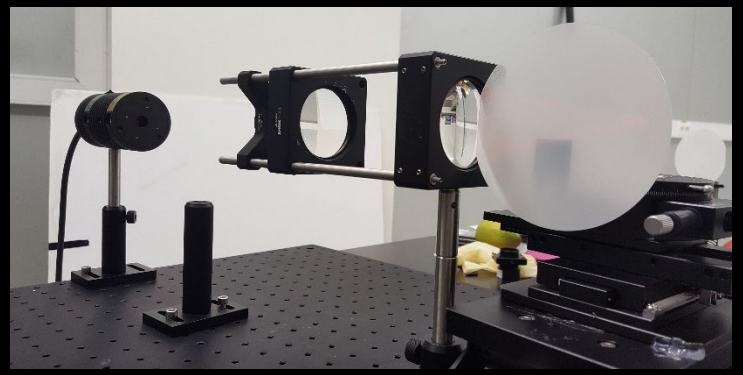
Compressive SPAD Camera—Results



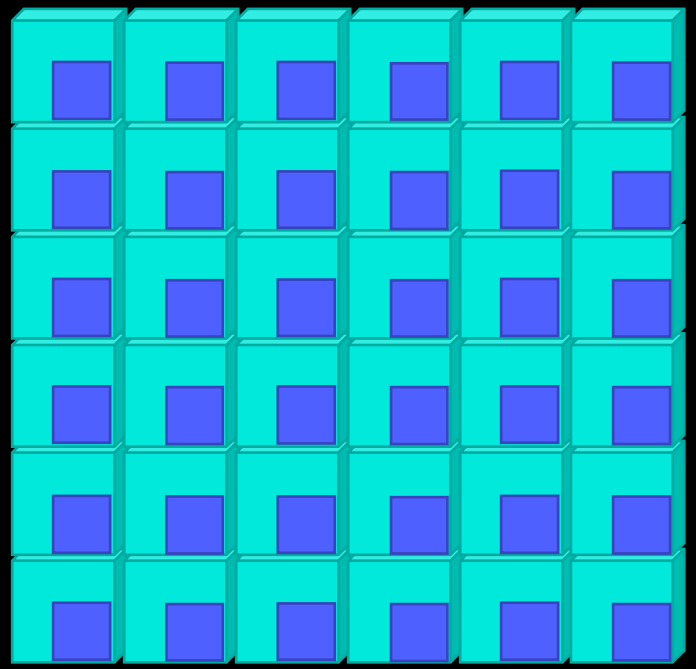




Compressive SPAD Camera—Results

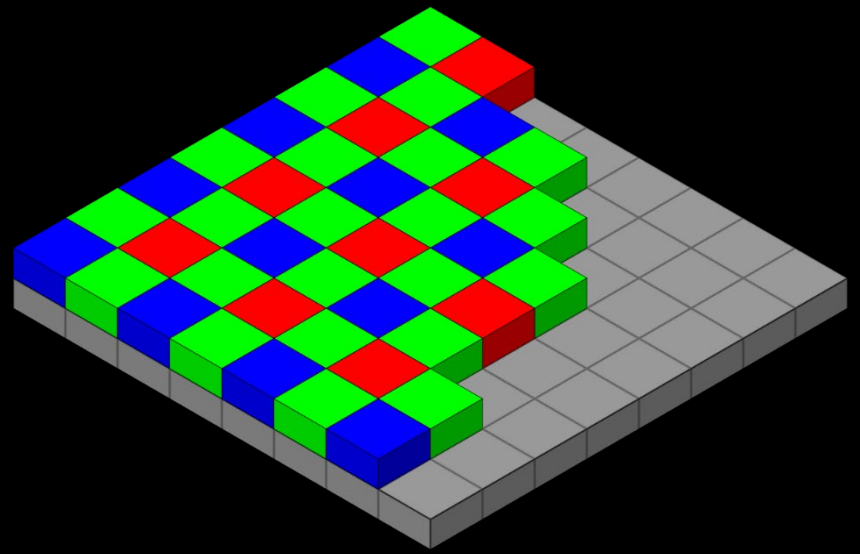


Sampling with a Physical Sensor Structure



Low fill-factor

- Aliasing artifacts
- Low efficient



Bayer filter

- Moiré pattern
- Mosaicing

Optimal Sampling for

Demosaicing

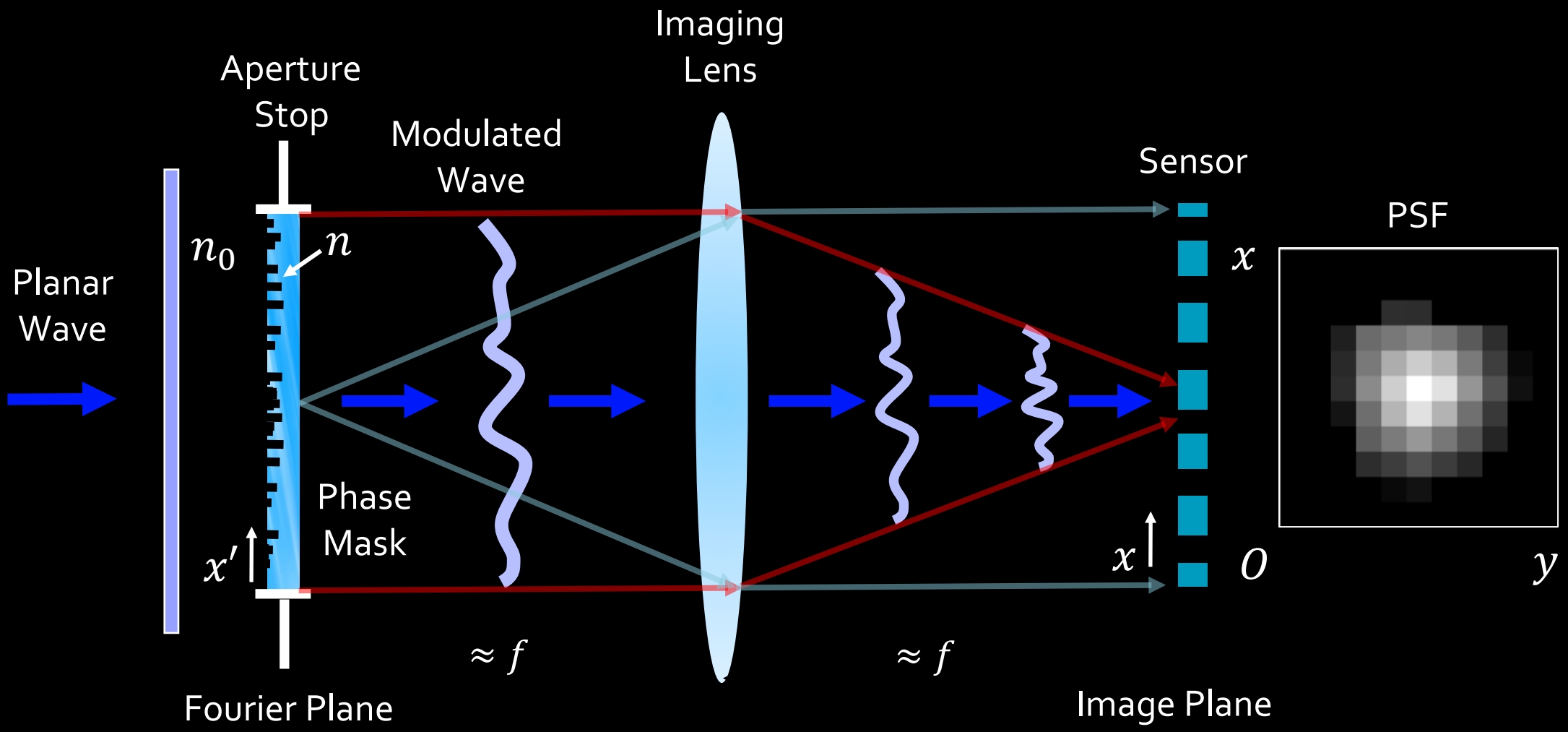
Anti-aliasing

Super-resolution

⋮

Etc.

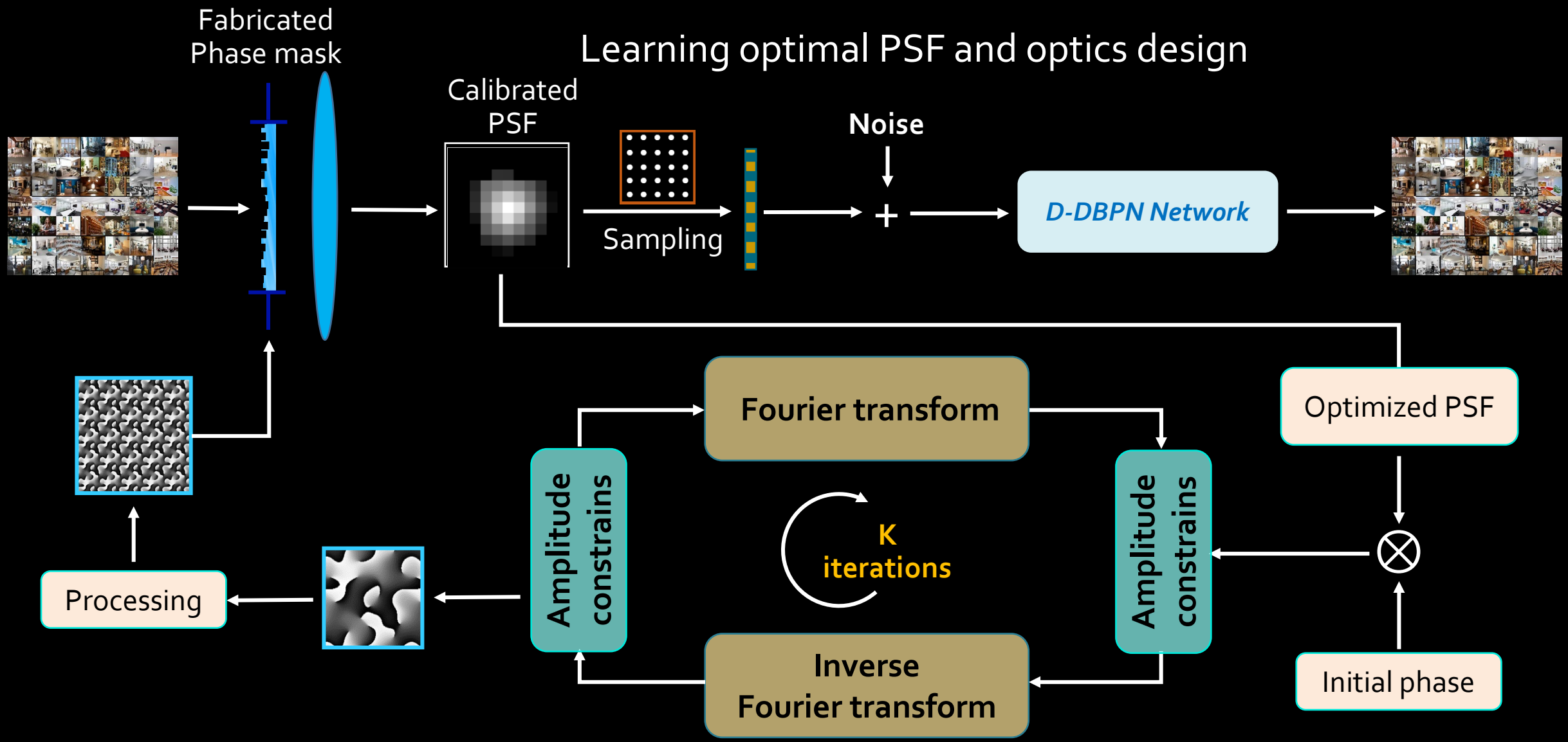
Optical Model



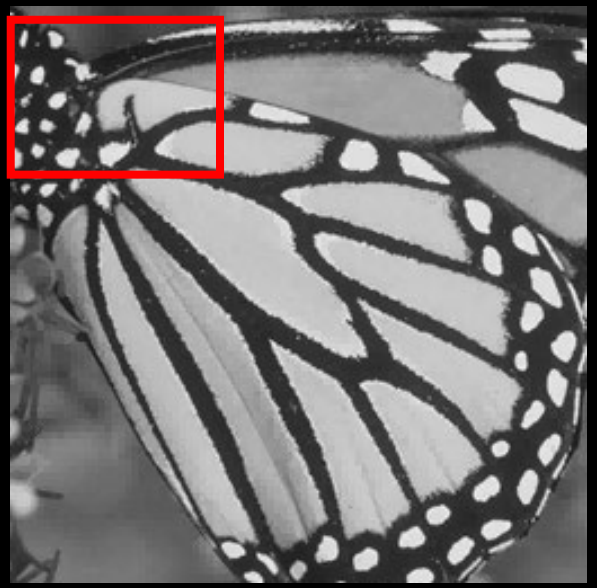
$\phi(x', y')$

$\rho_\lambda(x, y) \propto \|\mathcal{F}\{\phi(x', y')\}\|^2$

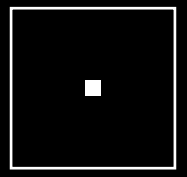
End-to-end Framework of SR SPAD Camera



Effectiveness of the Encoding Phase Mask



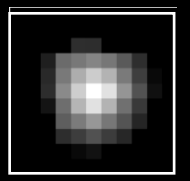
model	Set5 PSNR/SSIM	Set14 PSNR/SSIM	BSDS100 PSNR/SSIM
Low fill-factor	27.17/ 0.9019	23.97/ 0.8066	23.82/ 0.7691
Full fill-factor	29.77/ 0.9317	26.13/ 0.8442	25.59/ 0.8069
Ours	30.76/ 0.9399	26.91/ 0.8557	26.23/ 0.8198



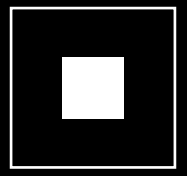
Low fill-factor

Low fill-factor (no mask)

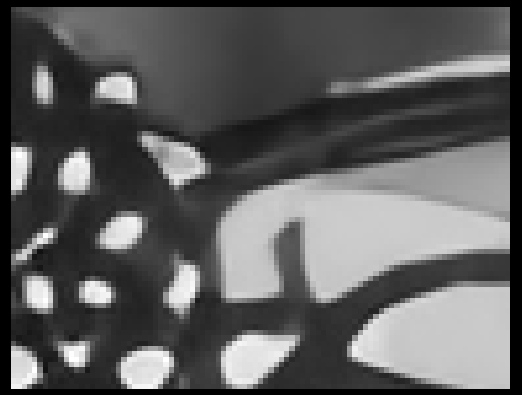
With phase mask



Ours



Full fill-factor



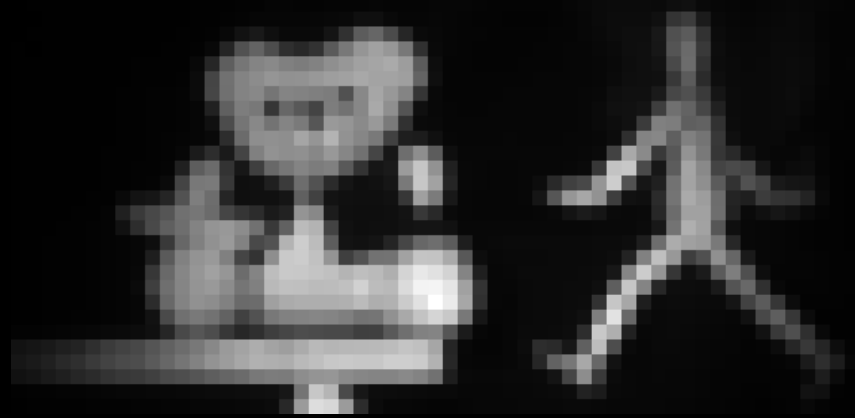
Full fill-factor

Ground Truth

Effectiveness of the Encoding Phase Mask

Raw image without mask

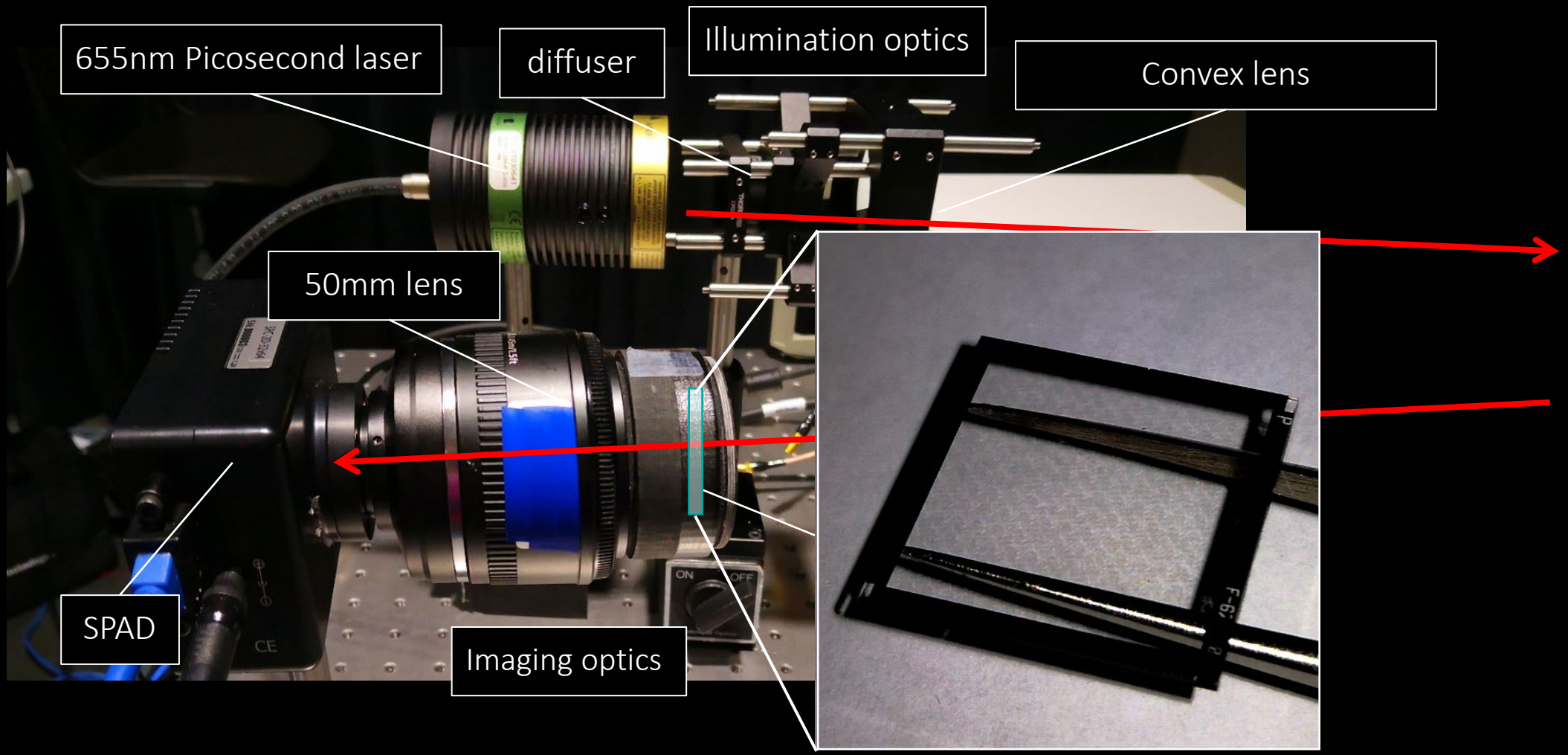
Result without mask



Raw image with mask

Result with mask

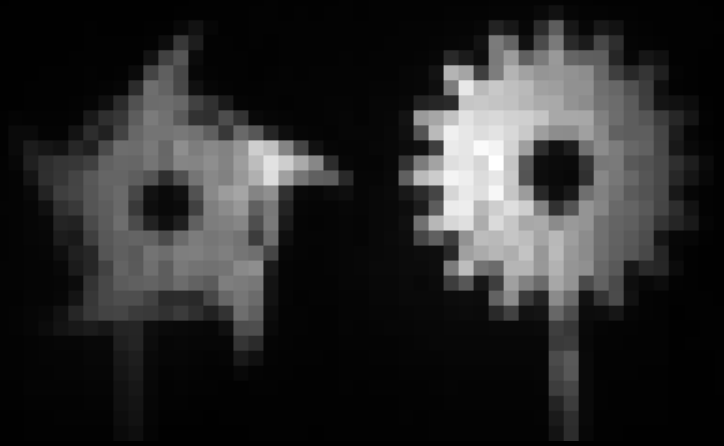
Prototype System



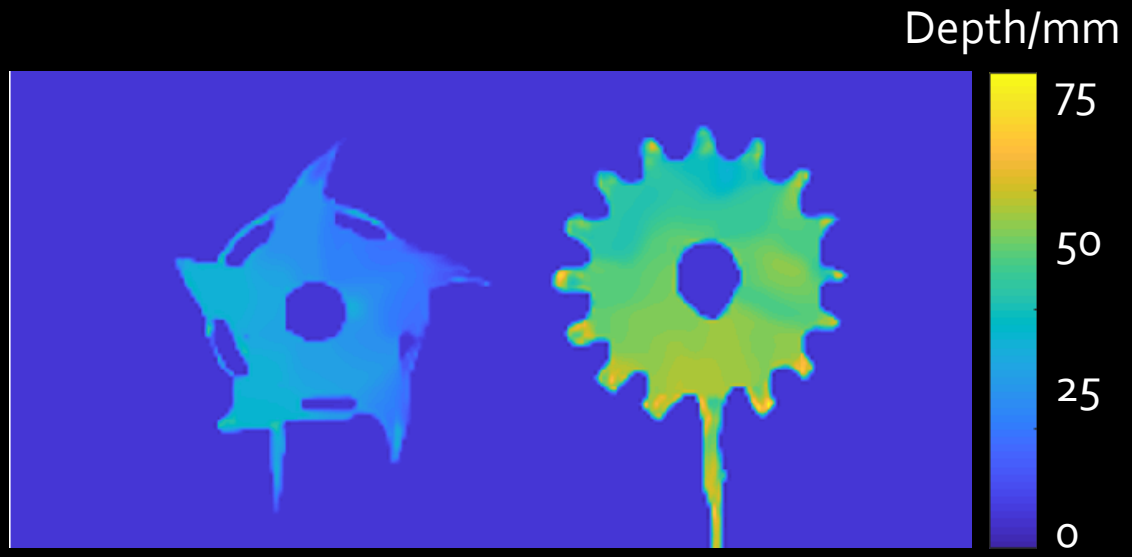
Applications: Intensity Imaging

Integration time 5.2ms

Applications: Depth Imaging



SPAD measurement
summed over time axis



Reconstruction depth map

Applications: Transient Imaging

Scene

SPAD measurement
(time resolved 20ps)

Reconstruction result

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Step Three: Enabling Comprimization for Color Channels

Learning Rank-1 Diffractive Optics for Single-shot High Dynamic Range Imaging

Limited Sensor Dynamic Range

Over Exposured

Under Exposured

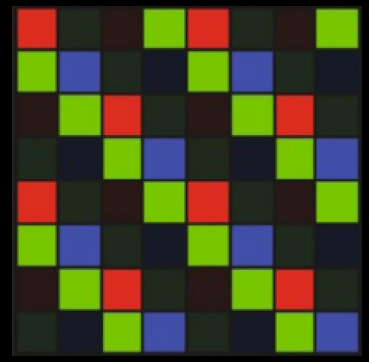
Traditonal Method—Burst Imaging

- Motion artifacts
- Long capture and processing time

Open Problem in HDR Imaging

Burst exposures

[Wan12]



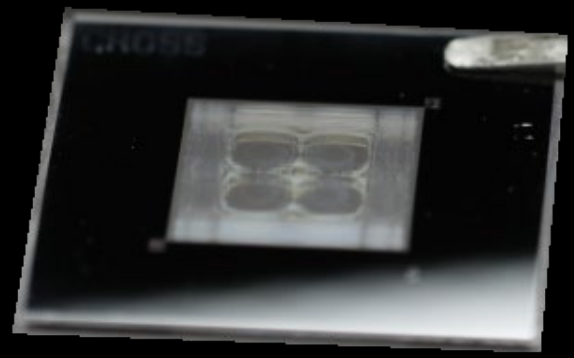
Deep L

Open Problem in HDR Imaging

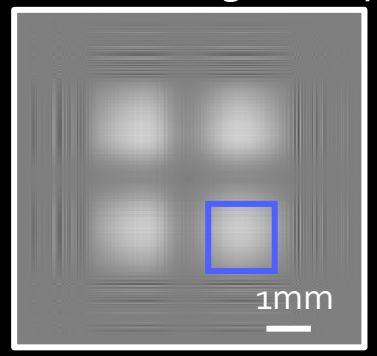
Single-shot HDR imaging using jointly learned optic + neural network

Prototype

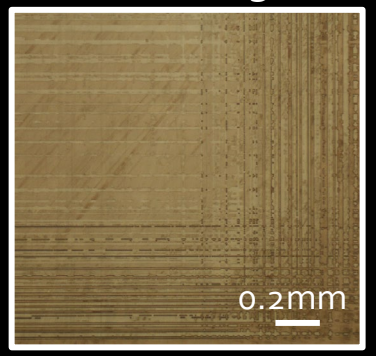
Fabricated learned optic



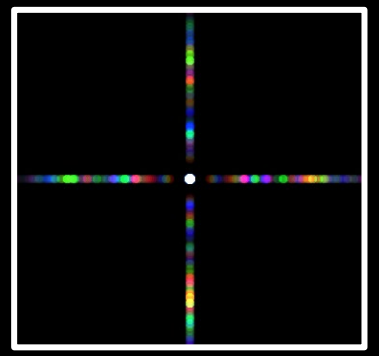
Simulated Height Map



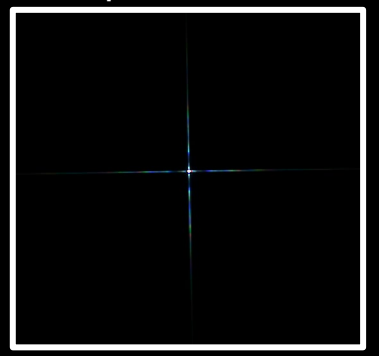
Fabricated Height Map



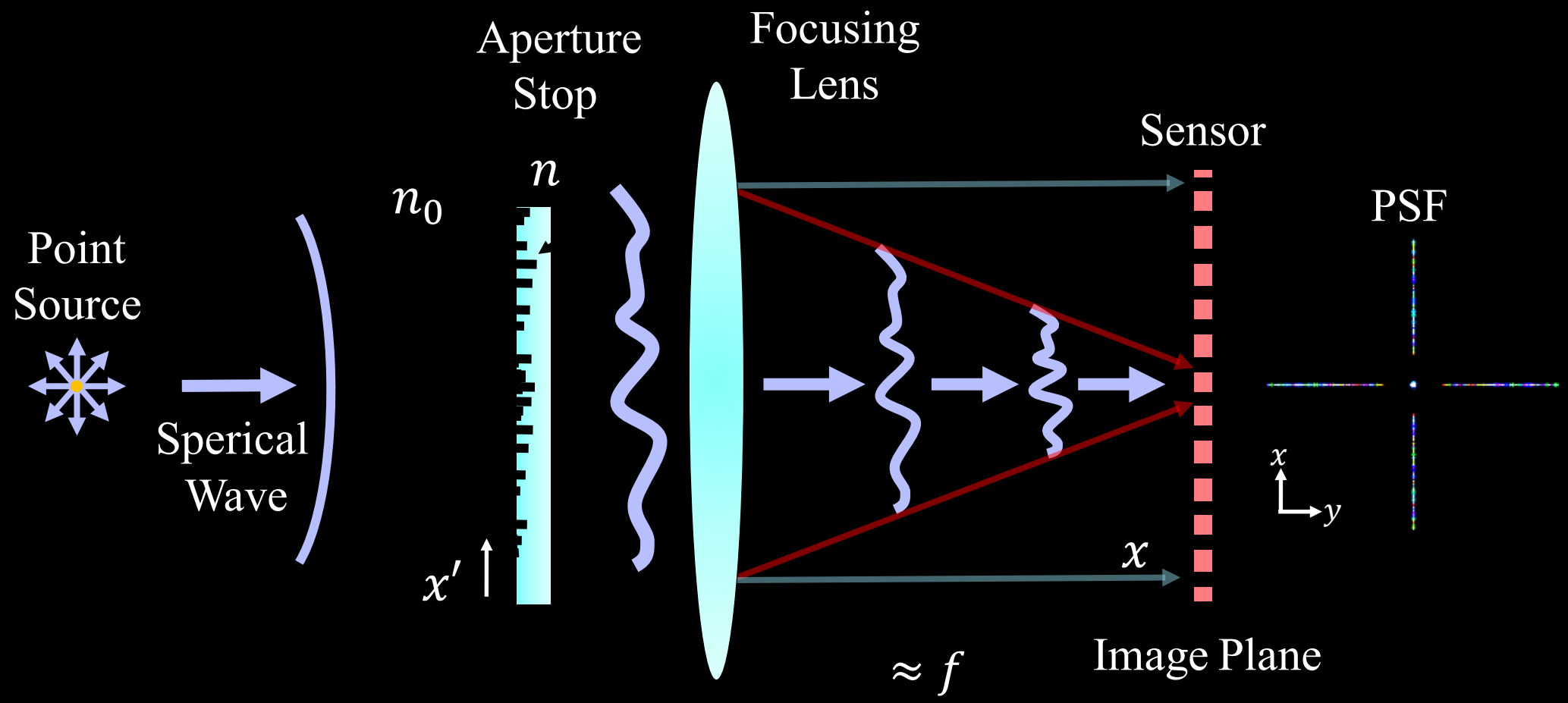
Simulated PSF



Captured PSF



Color-comprimised Optical Model



End-to-End HDRI Pipeline

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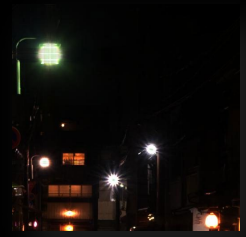


Image Formation Model

PSF

Sensor Model

$\mathbf{I}$

$\mathbf{I}_s$

Feature Extraction

VGG Features

Dilated Full-Resolution Reconstruction Block

Recovered Unsaturated Region

$\mathcal{L}_{\mathbb{U}}$

Residual

HDR Fusion

conv

conv

concat

conv

conv

conv

conv

$\mathcal{L}_{\mathbb{F}}$

Residual-Refinement

Recovered Saturated Region

$\mathcal{L}_{\mathbb{S}}$

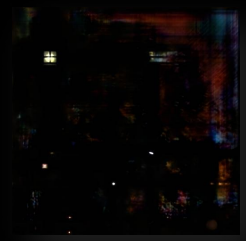
Phase

Capture

Prototype

Fabrication

Rank-1 Factorization



Learning Rank-1 Diffractive Optics

- Point Light Source

$$\mathbf{u}_{-} = A_0 e^{jk\sqrt{x'^2+y'^2+z^2}}$$

- DOE Layer and Rank-1 Factorization

$$\mathbf{u}_{+} = \mathcal{A}(x', y')\mathbf{u}_{-} e^{jk(n_\lambda - 1)\mathbf{h}(x', y')}$$

- Heightmap

$$\mathbf{h}(x', y') = h_{\max}\, \sigma\left(\mathbf{v}\mathbf{q}^{\top}\right)$$

Trainable parameters: $\mathbf{v} \in \mathbb{R}^{m\times 3}$ $\mathbf{q} \in \mathbb{R}^{m\times 3}$

- Fresnel Propagation

$$\mathbf{u}_s = \mathcal{F}^{-1}\{\mathcal{F}\{\mathbf{u}_l\}\mathcal{H}\}$$

$$\mathcal{H}(f_x, f_y) = e^{jkL} e^{-j\pi\lambda L(f_x^2+f_y^2)}$$

Loss Function

- Total Loss

$$\mathcal{L}_{\text{Total}} = \mathcal{L}_{\mathbb{U}} + \mathcal{L}_{\mathbb{S}} + \mathcal{L}_{\mathbb{F}}$$

- Loss on Unsaturated Regions
  - VGG Loss $\mathcal{L}_{\text{VGG}}(\hat{x}, x) = \sum \nu_l \|\phi_l(\hat{x}) - \phi_l(x)\|_1$
  - Exclusion loss $\mathcal{L}_{\text{excl}} = \|\tanh(\eta_{\mathbb{U}} \mid \nabla \hat{\mathbf{I}}_{\mathbb{U}} \mid) \odot \tanh(\eta_r \mid \nabla \hat{\mathbf{I}}_r \mid)\|_F$
- Loss on Saturated Region

$$\mathcal{L}_{\mathbb{S}} = \beta \mathcal{L}_{\text{VGG}}(\hat{\mathbf{I}}_{\mathbb{S}}, \mathbf{I}_{\mathbb{S}})$$

- Loss in Fused Output

$$\mathcal{L}_{\mathbb{F}} = \mathcal{L}_{\text{Huber}}\left((\hat{\mathbf{I}} + \epsilon)^{\gamma}, (\mathbf{I} + \epsilon)^{\gamma}\right)$$

Simulated Results

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点明 POINT SPREAD

HDR-CNN | Glare-HDR | Deep Optics | Our Measurement | Our Reconstruction | Reference HDR

Simulated Results

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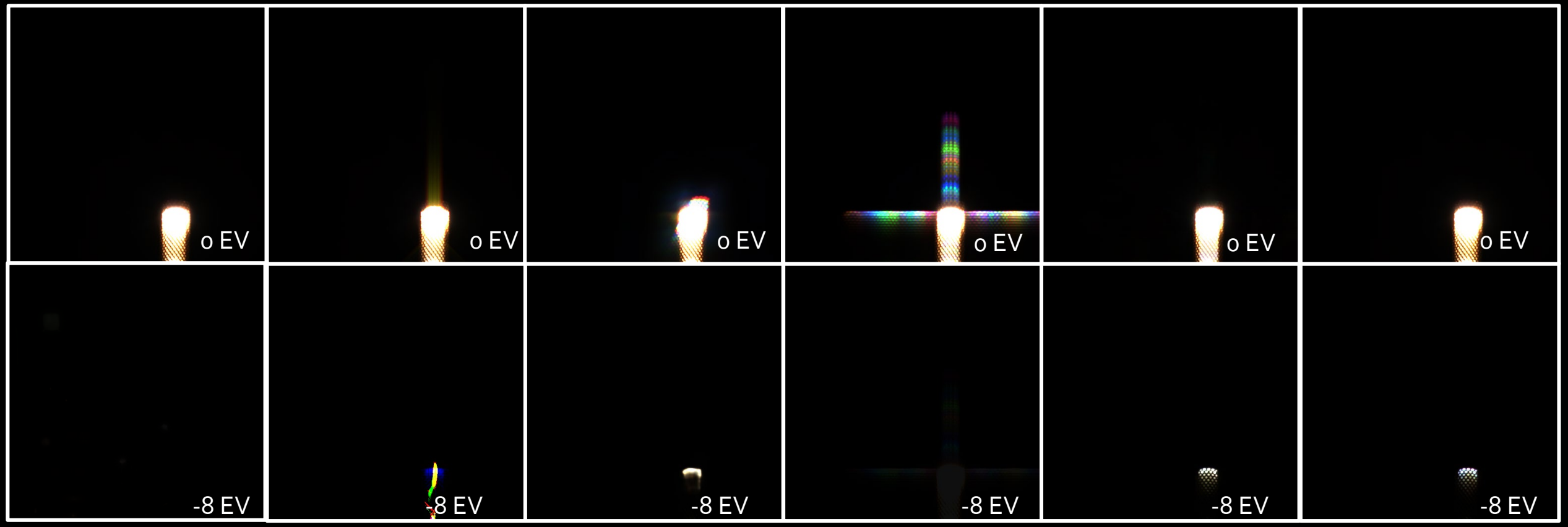
点明 POINT SPREAD



Comparison in Simulation

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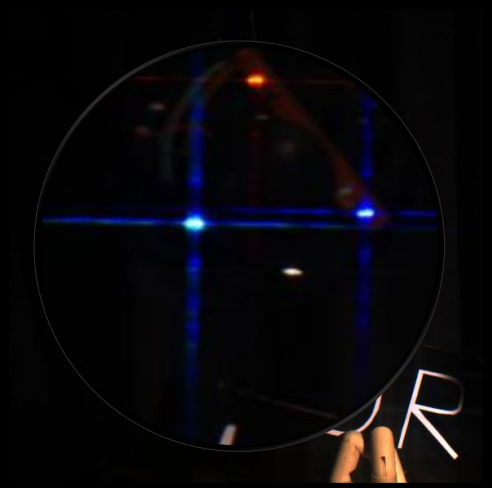
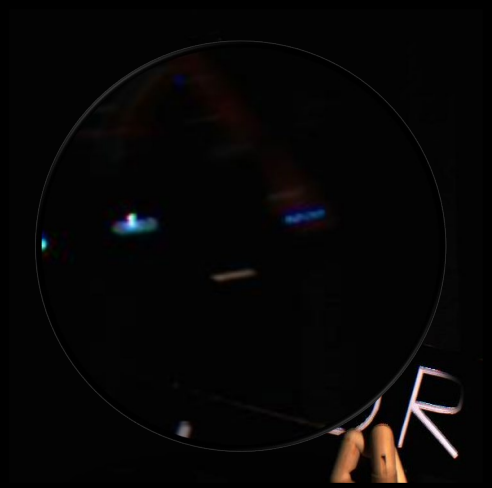
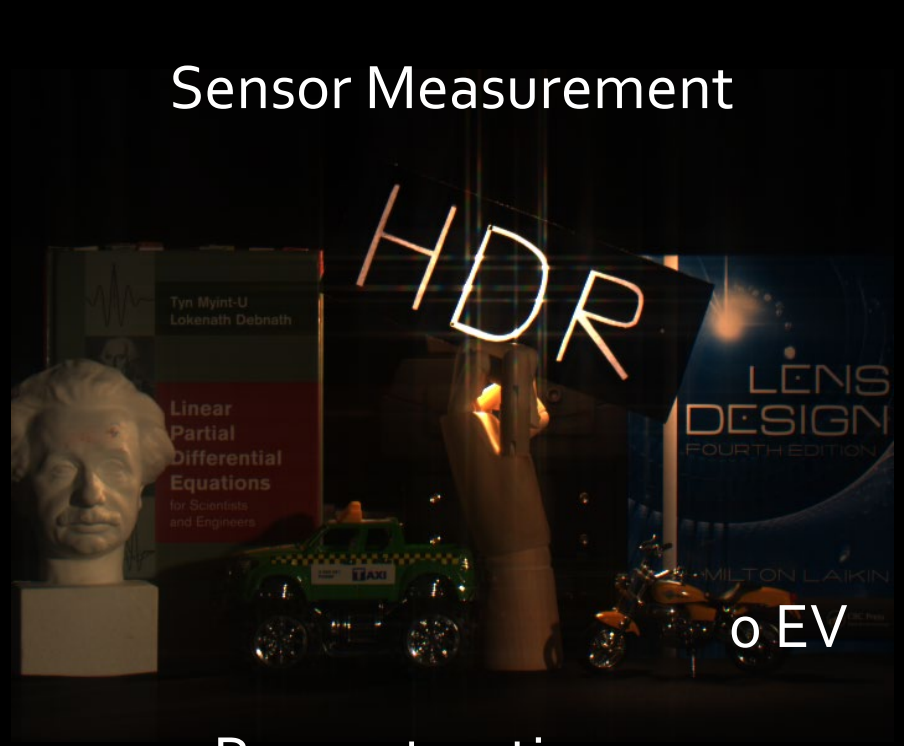
Methods	PSNR	HDR-VDP 2
Ours	48.26	74.47
Deep Optics	40.30	67.96
Glare-HDR	32.23	56.76
HDR-CNN	34.06	54.34
LDR	33.57	52.43





Sensor Measurement



Reconstruction

Measurement	Reconstruction	Reference
-4 EV	-4 EV	-4 EV
-6 EV	-6 EV	-6 EV

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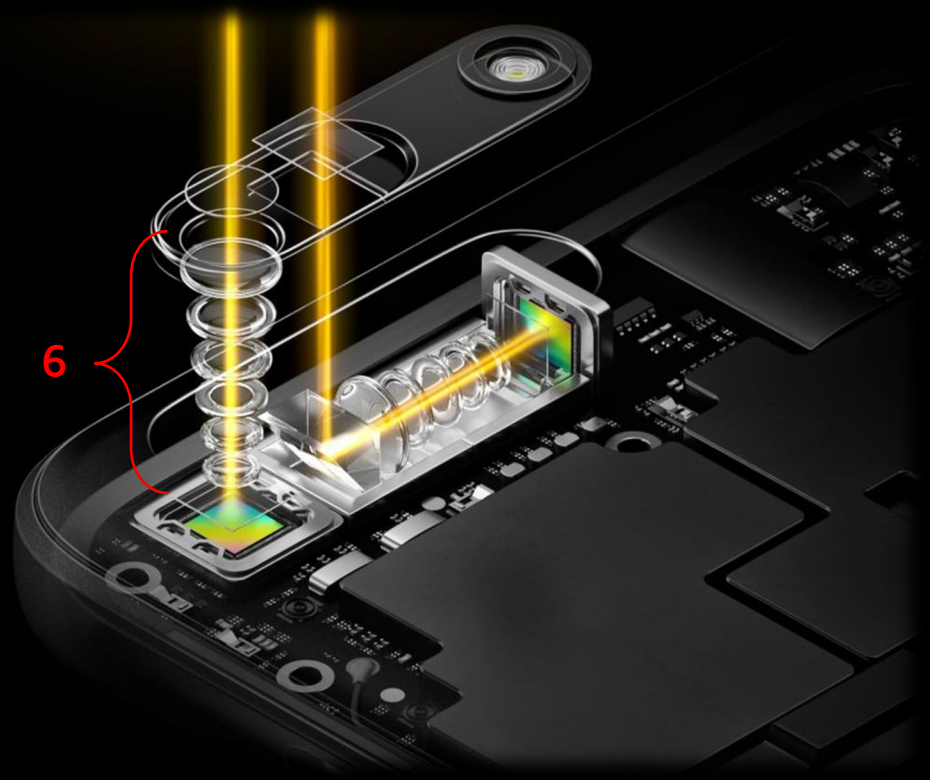
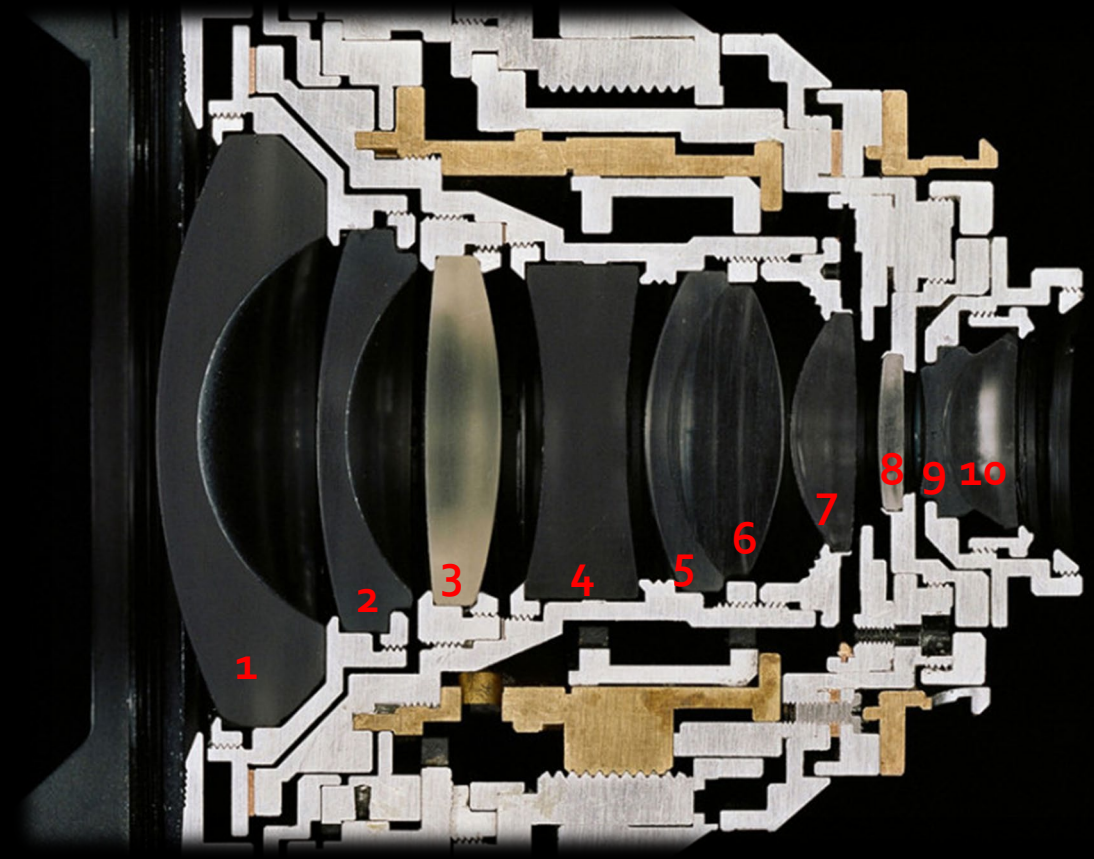
Measured	Recovered	Reference	Measured	Recovered	Reference
					
					
					

Step Four: End-to-end Complex Lens Design

End-to-End Complex Lens Design with Differentiable Ray Tracing

Complex Lens Systems





- High quality imaging combat with aberrations of all kinds
- Sometimes not optimal for a given task

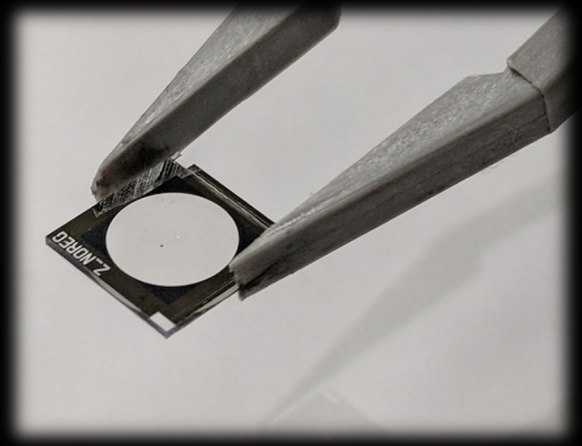
** Images credits @ Oppo, Nikon*

End-to-end Optics Designing

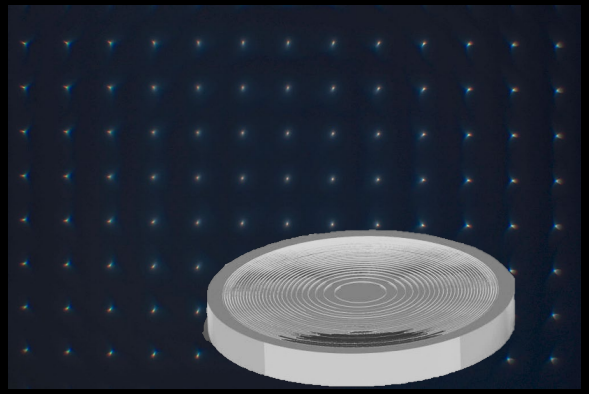
- Diffractive optics
- Refractive optics

- Thin form factor

- Single layer differentiable
- Paraxial approximation
- Limited design freedom
- Limited image quality
- Not fully differentiable

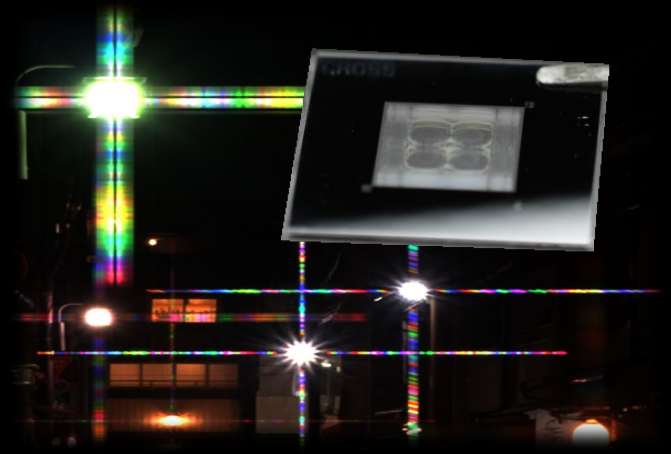


[Sitzmann et al. 2018]



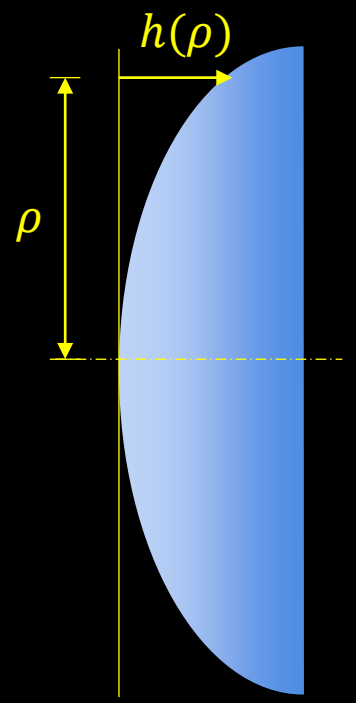
[Peng et al. 2019]

[Sun et al. 2020]



[Sun et al. 2020]

Differentiable Lens Model and Ray Tracer



- Aspherical Lenses:

$$h(\rho) = \frac{c\rho}{1+\sqrt{1-\alpha\rho}} + \sum_{i=2}^{n} a_{2i}\rho^{i} \qquad \alpha = (1+\kappa)c^2$$

- Aspherical Lenses's Derivative:

$$h'(\rho) = \mathrm{c}\frac{1+\sqrt{1-\alpha\rho}-\alpha\rho/2}{\sqrt{1-\alpha\rho}(1+\sqrt{1-\alpha\rho})^2} + \sum_{i=2}^{n} i a_{2i}\rho^{i-1}$$

- Implicit form $f(x,y,z)$ and its derivative:

$$f(x,y,z) = h(\rho) - z$$

$$\nabla f = (2h'(\rho)x, 2h'(\rho)y, -1)$$

Differentiable Lens Model and Ray Tracer

- Ray-surface Intersection by Newton's Method: Ray(**o, d**)
  - Find the t>o such that:

$$f(x, y, z) = f(\mathbf{o} + t\mathbf{d}) = 0$$

  - We solve the problem numerically using Newton's method

$$t^{(k+1)} \leftarrow t^{(k)} - \frac{f(\mathbf{o} + t^{(k)}\mathbf{d})}{f'(\mathbf{o} + t^{(k)}\mathbf{d})}$$

$$\leftarrow t^{(k)} - \frac{f(\mathbf{o} + t^{(k)}\mathbf{d})}{\nabla f \cdot \mathbf{d}}$$

- Dispersion extention of Mitsuba2 by Cauchy's equation

$$n(\lambda) = A + \frac{B}{\lambda^2} + \frac{C}{\lambda^4} + \ldots \qquad A = n_D - \frac{B}{\lambda_D^2} \qquad B = \frac{n_D - 1}{V(\lambda_F^{-2} - \lambda_C^{-2})} \quad \ldots$$

Differentiable Lens Model and Ray Tracer

- Recorded image on sensor:

$$I_c(x', y') = \int Q_c(\lambda)[p(x', y', d, \lambda) * s_c(x', y', d)]d\lambda + n(x', y')$$

- Monto Carlo Sampling
- Image auto alignment during training:
  - The relationship between traced points on sensor $\boldsymbol{r}_d$ and ideal points $\boldsymbol{r}$ can be expressed as:

$$\boldsymbol{r}_d = \zeta \boldsymbol{r}(1 + k_1\boldsymbol{r}^2 + k_2 4 + k_3\boldsymbol{r}^6)$$

  - We solve a least square problem to obtain the current distortion coefficients and magnification.

$$\min_{\boldsymbol{K}} \left\| [\boldsymbol{r}, \boldsymbol{r}^3, \boldsymbol{r}^5, \boldsymbol{r}^7]\boldsymbol{K}^T - \boldsymbol{r}_d \right\|_2^2$$

Differentiable Complex Lens and Recovery

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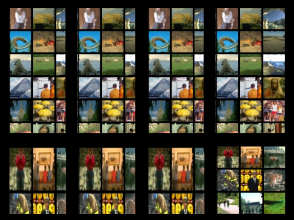
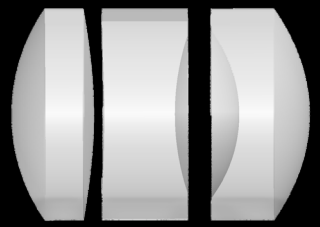
Scene Dataset

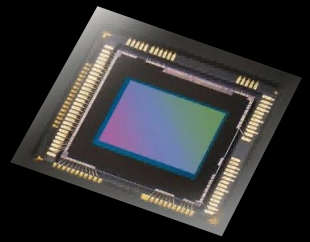


Complex Lens Model

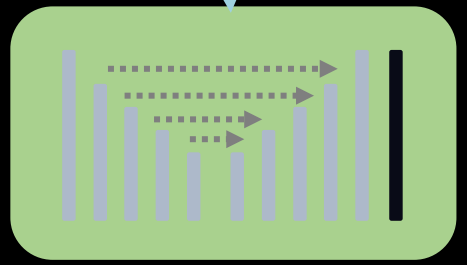


differentiable ray-tracing

Simulated Sensor



Loss



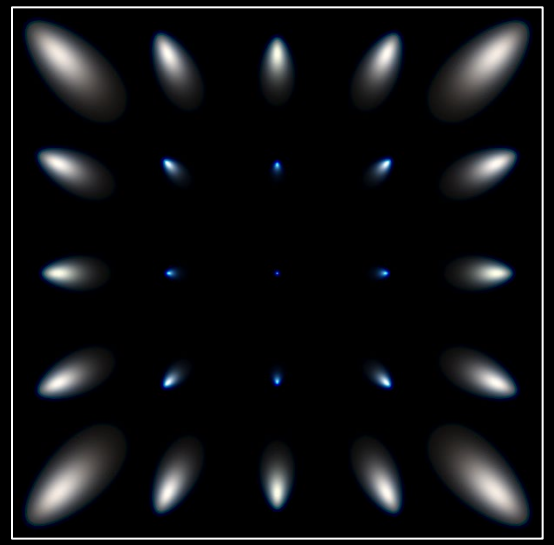
Real Scene

Prototype

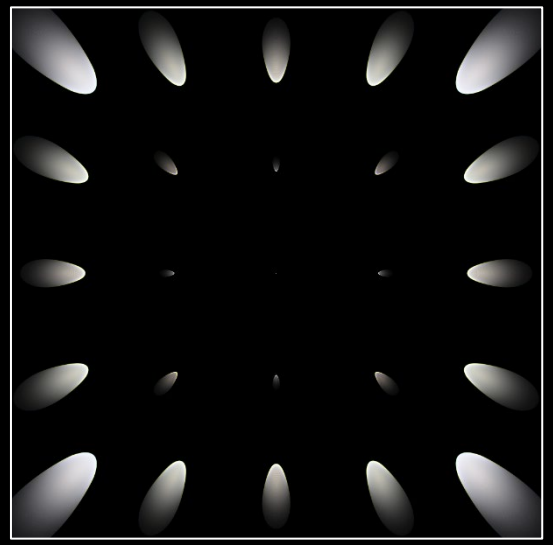
Image Recovery Network

Large Field-of-View Imaging

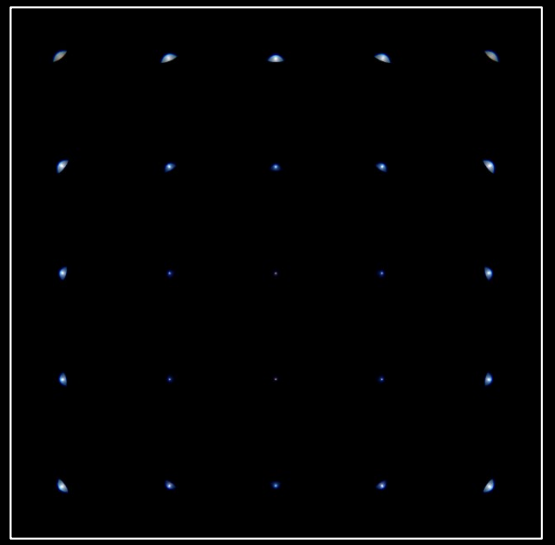
AL2550



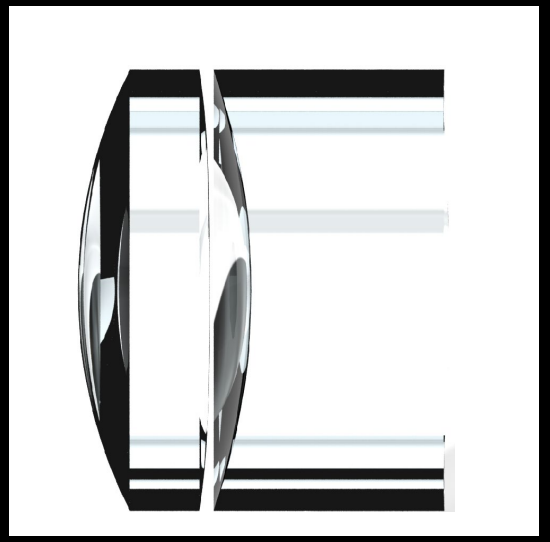
ACA254

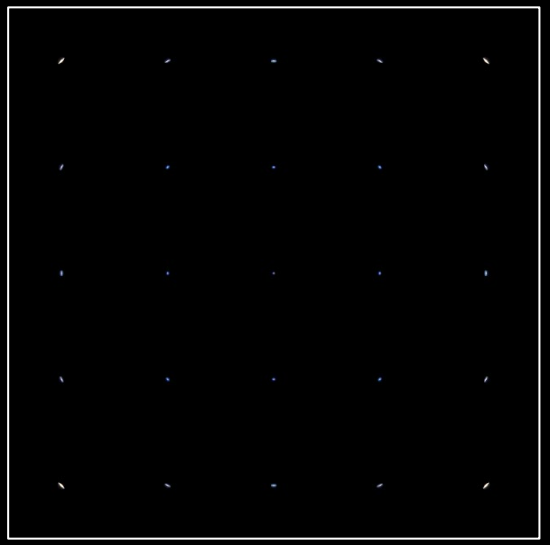


Peng et al 2019



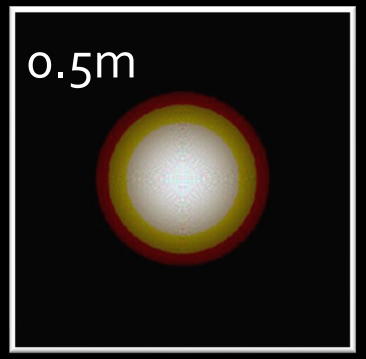
Ours

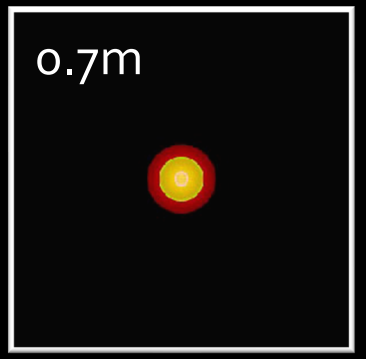


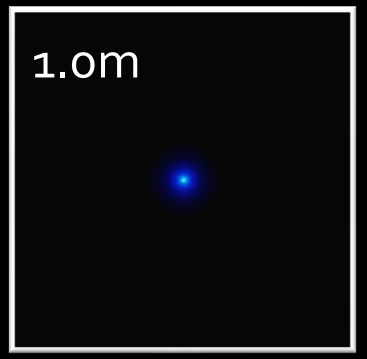


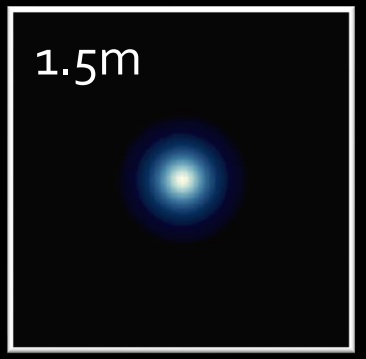
Extended Depth-of-Field

AL2550









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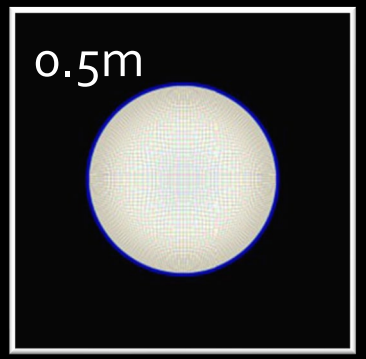
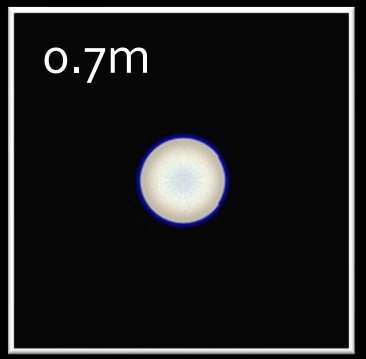
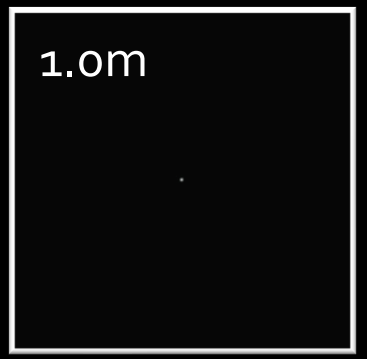
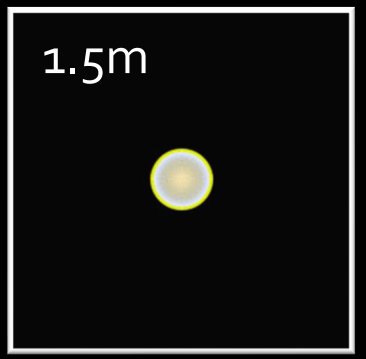
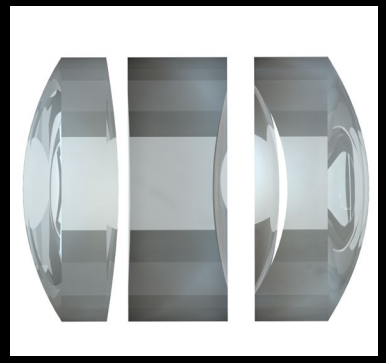


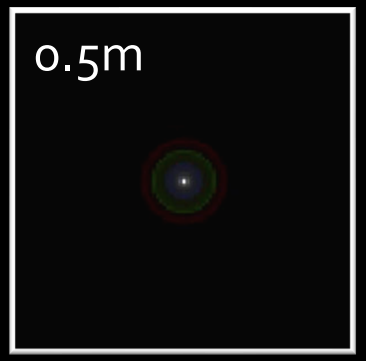


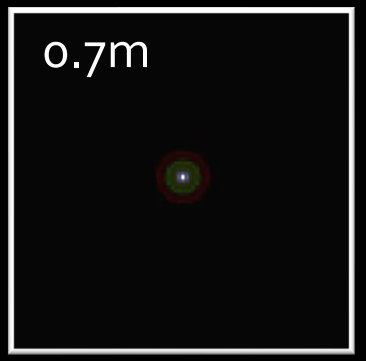




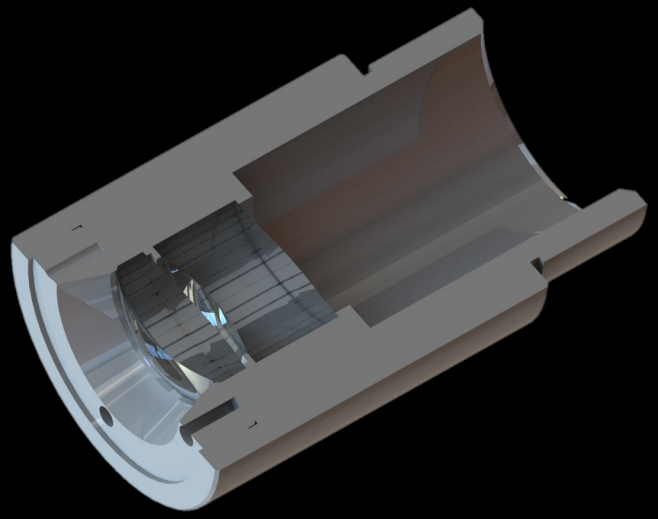
Ours



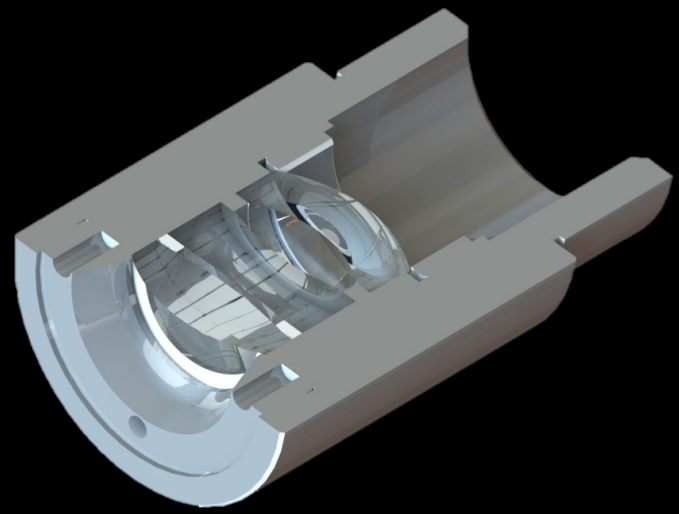




Prototypes

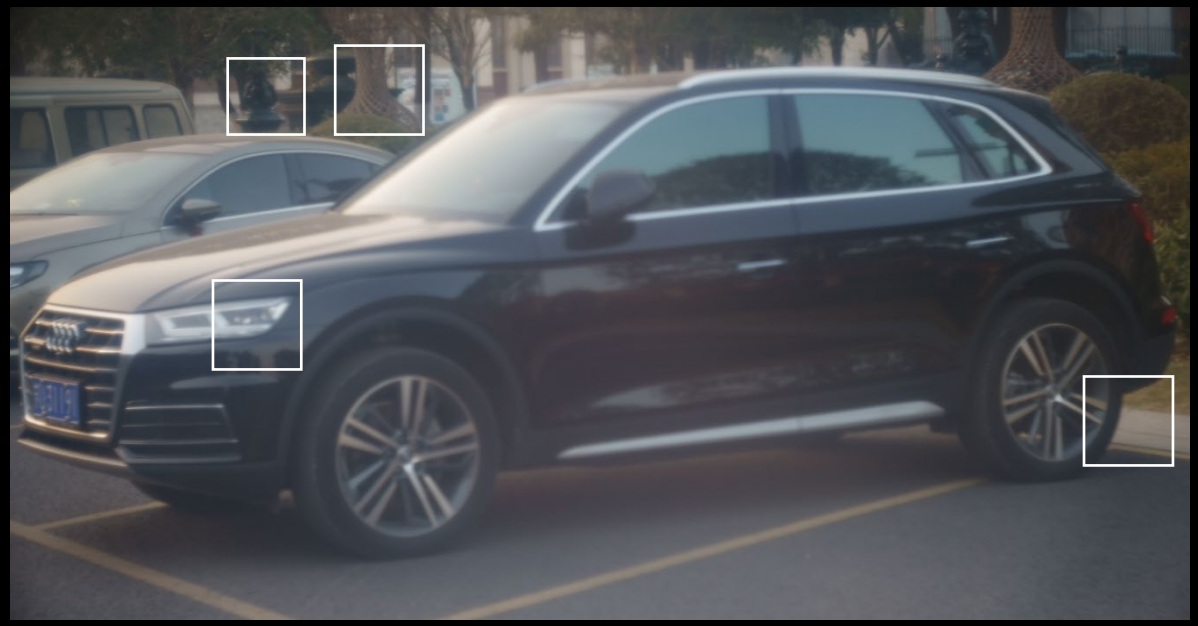


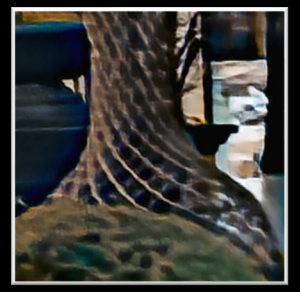
50mm/f4



50mm/f4

Results of Large Field-of-View Imaging

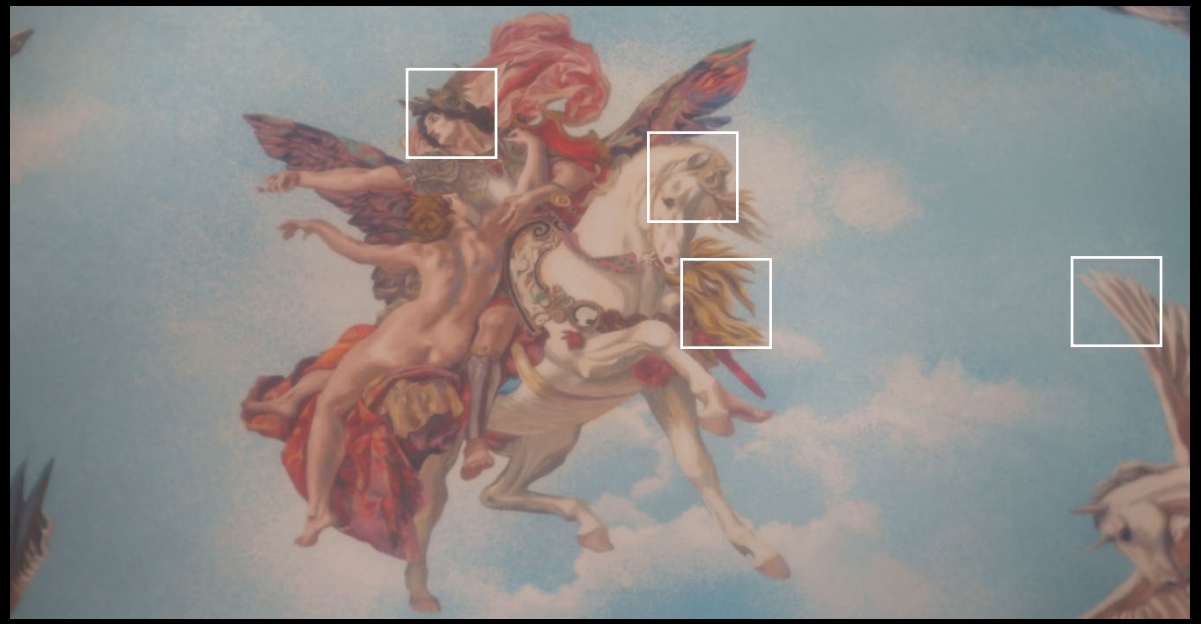


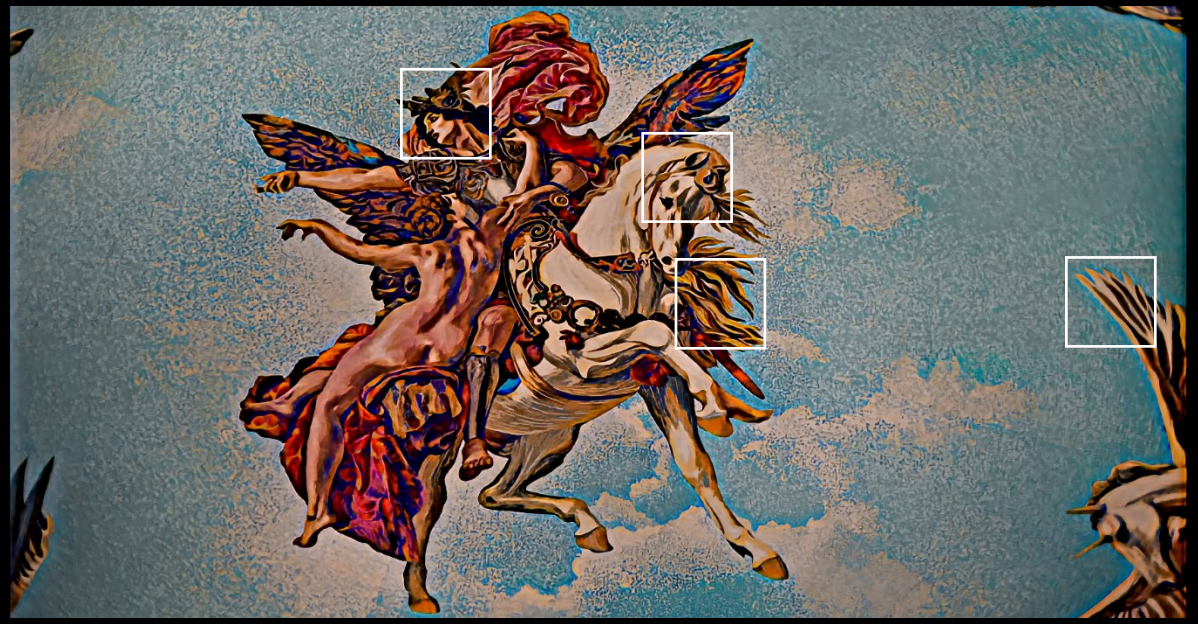


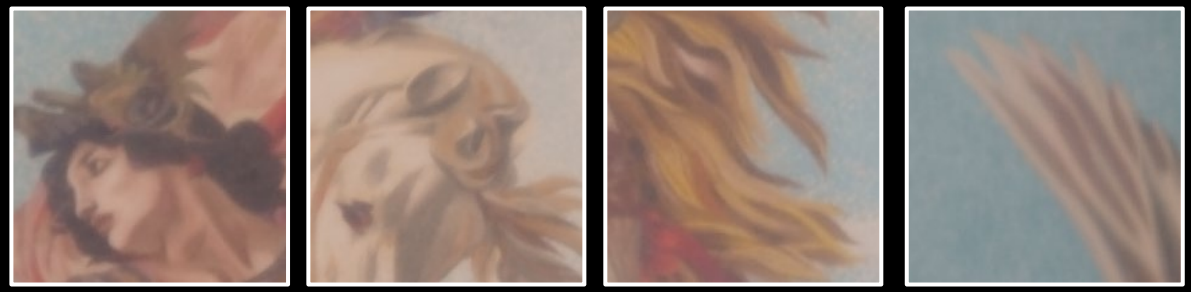
Captured

Recovered

Results of Large Field-of-View Imaging







Captured

Recovered

Results of Extended Depth-of-Field

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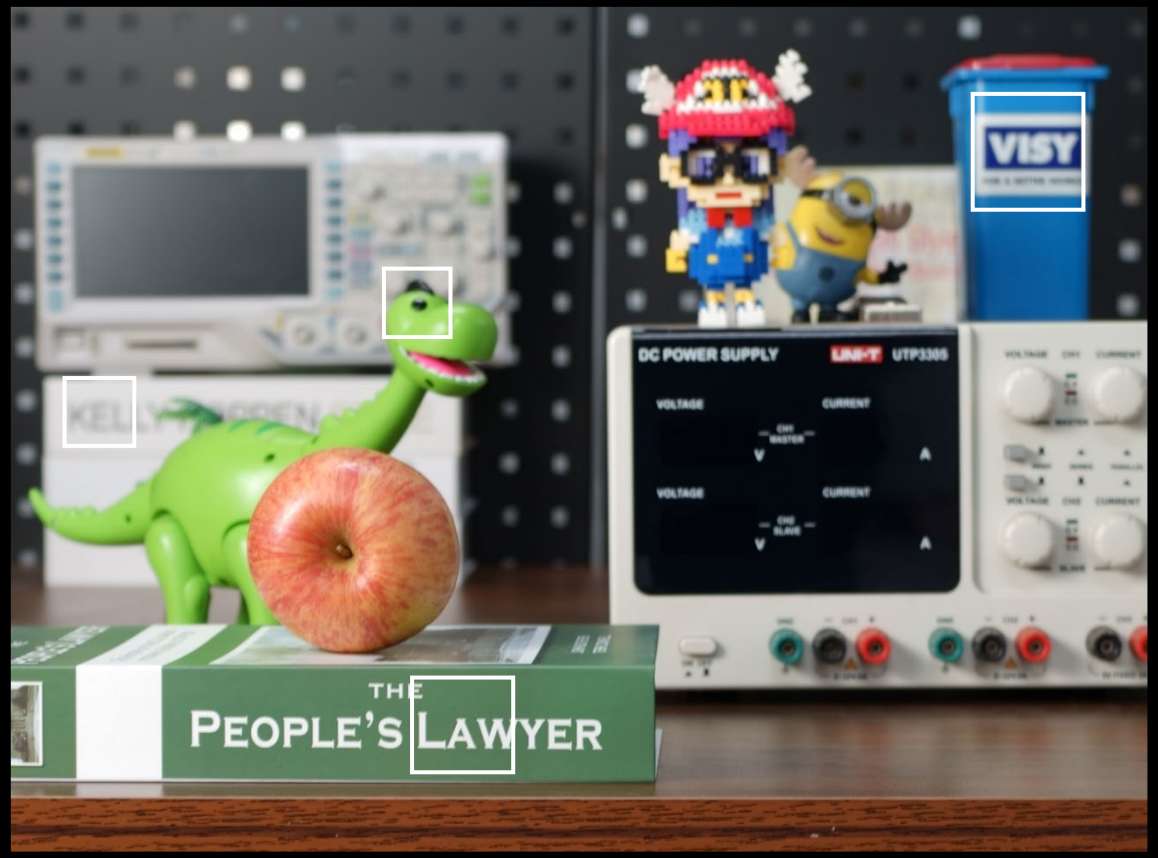
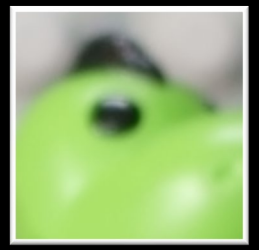
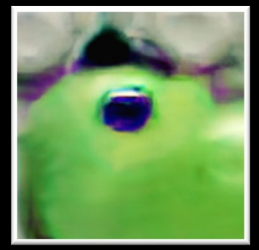




Sony standard zoom lens at *50mm/f4.5*



Ours at *50mm/f4*

Results of Extended Depth-of-Field

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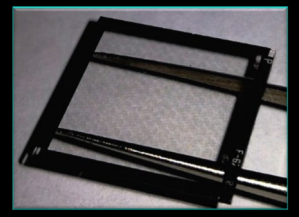
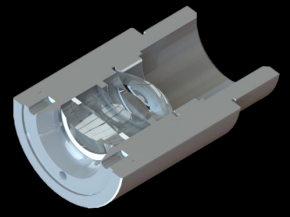
Ours at *50mm/f4*
Captured

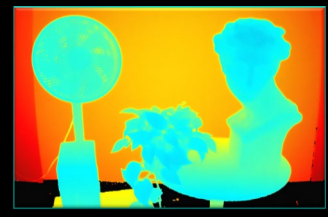
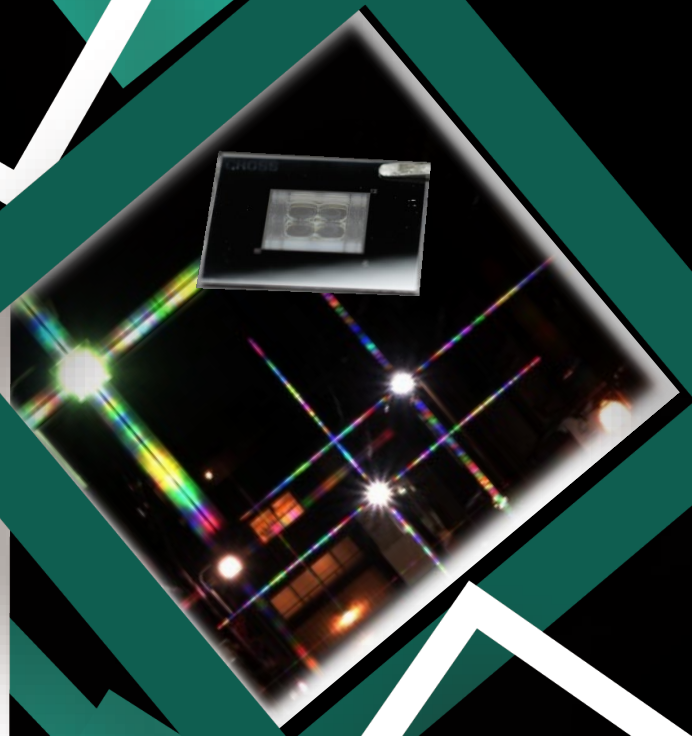
Ours at *50mm/f4*
Processed

Sony standard zoom lens
at *50mm/f4.5*

- Step One: Joint Optimization of Optics and Image Recovery
  - Learned Large Field-of-View Imaging with Thin-Plate Optics
- Step Two: Compressive and Optically Coded Super-resolution SPAD Camera
  - Compressive and Optically Coded Super-resolution SPAD Camera
- Step Three: Enabling Comprimization for Color Channels
  - Learning Rank-1 Diffractive Optics for Single-shot High Dynamic Range Imaging
- Step Four: End-to-end Complex Lens Design
  - End-to-end Complex Lens Design with Differentiable Ray-Tracing



Computational Imaging

Thank You!

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香港中文大学（深圳）

点昀技术（Point Spread Technology）