Polarization Multi-Image Synthesis with Birefringent Metasurfaces

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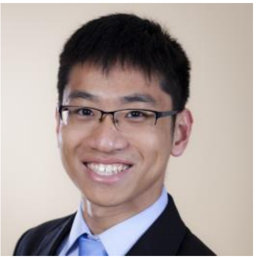
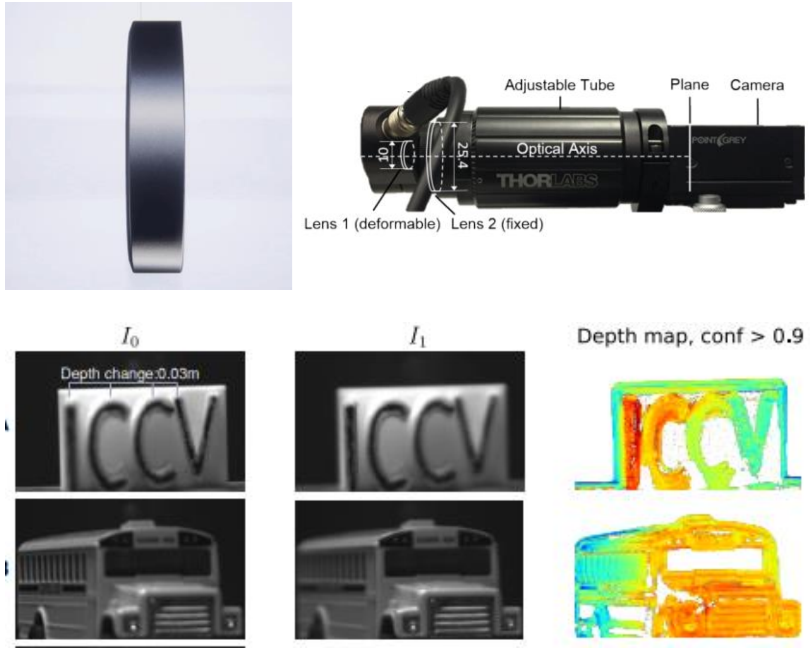



Motivation: Computing with Sets of Images

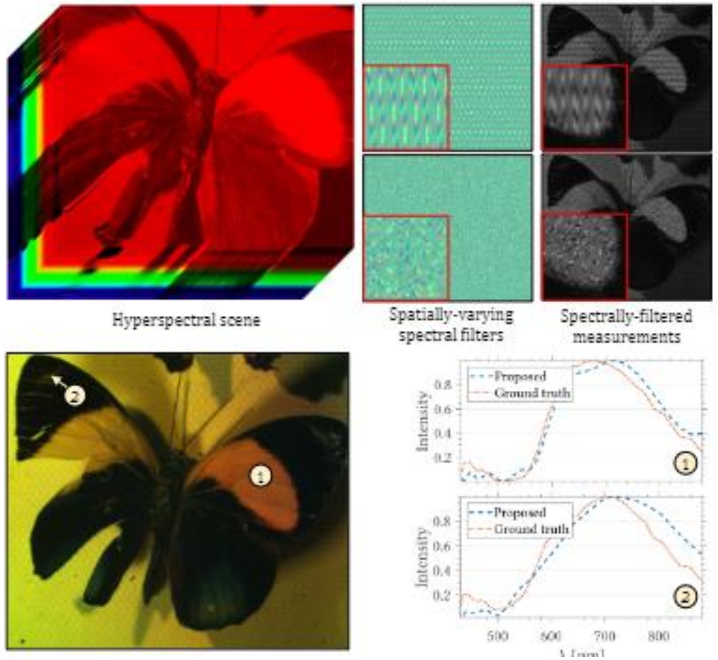
All computational imaging tasks have benefited from the capture and processing of multiple images

- Images captured **from the same perspective but with different optics**
- Images captured **from different viewpoints**

Depth-Sensing with Deformable Lens



Hyperspectral Imaging with SLM



https://www.optotune.com/machine-vision

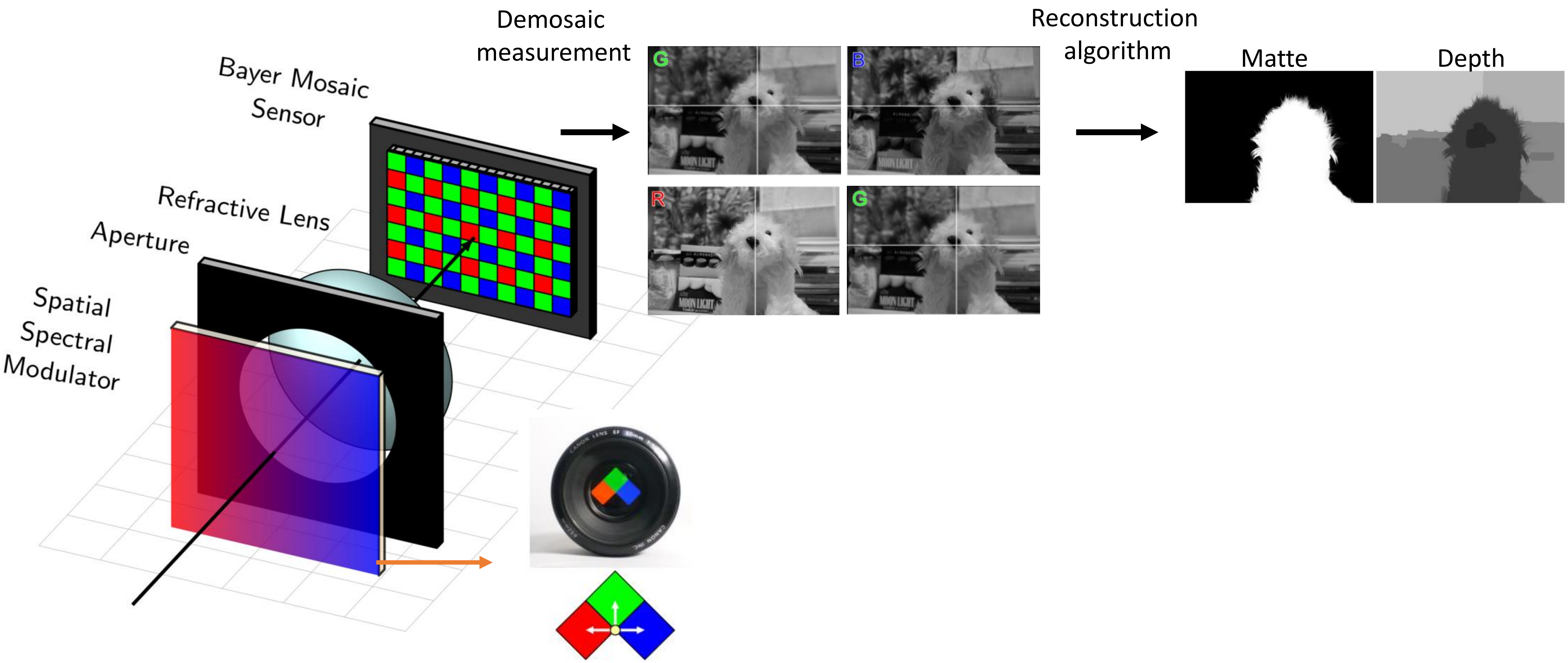
Guo, Q. et al., International Conference on Computer Vision (ICCV). IEEE (2017).

Saragadam V. et al, Programmable Spectral Filter Arrays using Phase Spatial Light Modulators, arxiv 2021

Snapshot **Spectral** Multi-Coded Imaging – Prior Works

Methods to capture multiple coded images in one exposure

Paradigm: Spectral filters as separate imaging channels



Demosaic measurement

Reconstruction algorithm

Matte

Depth

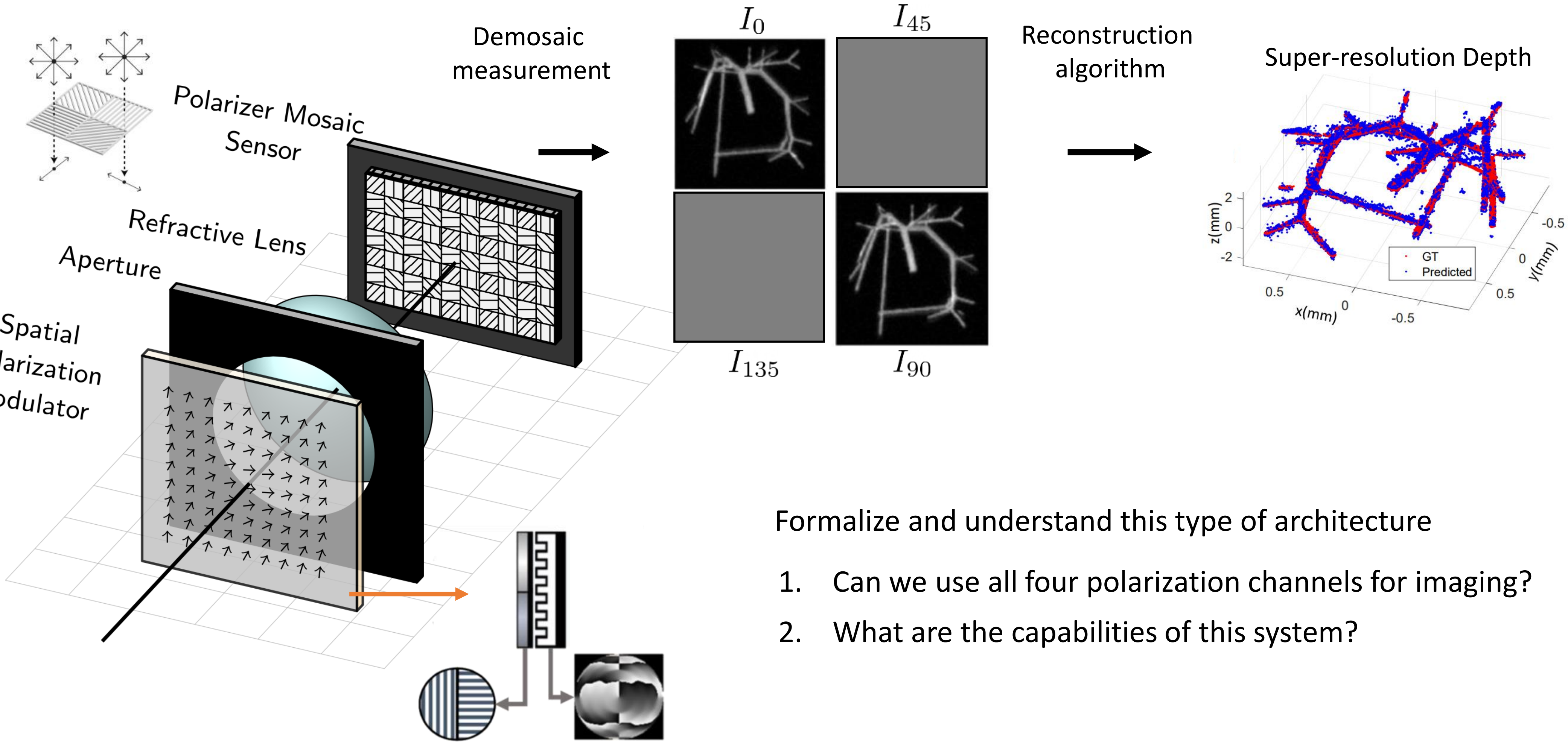
- Distinctly coded images on different wavelengths
- Mosaic of spectral filters at the sensor to retrieve set

[1] Y. Bando et al., Extracting Depth and Matte using a Color-Filtered Aperture, ACM Trans. Graph. 2008.
(See also) A. Chakrabarti et al, ECCV 2012. (and) C. Corre et al., Journal of the Optical Society of America, 2015

Snapshot **Polarization** Multi-Coded Imaging – New Opportunities

Methods to capture multiple coded images in one exposure

New Paradigm: Polarization as imaging channels

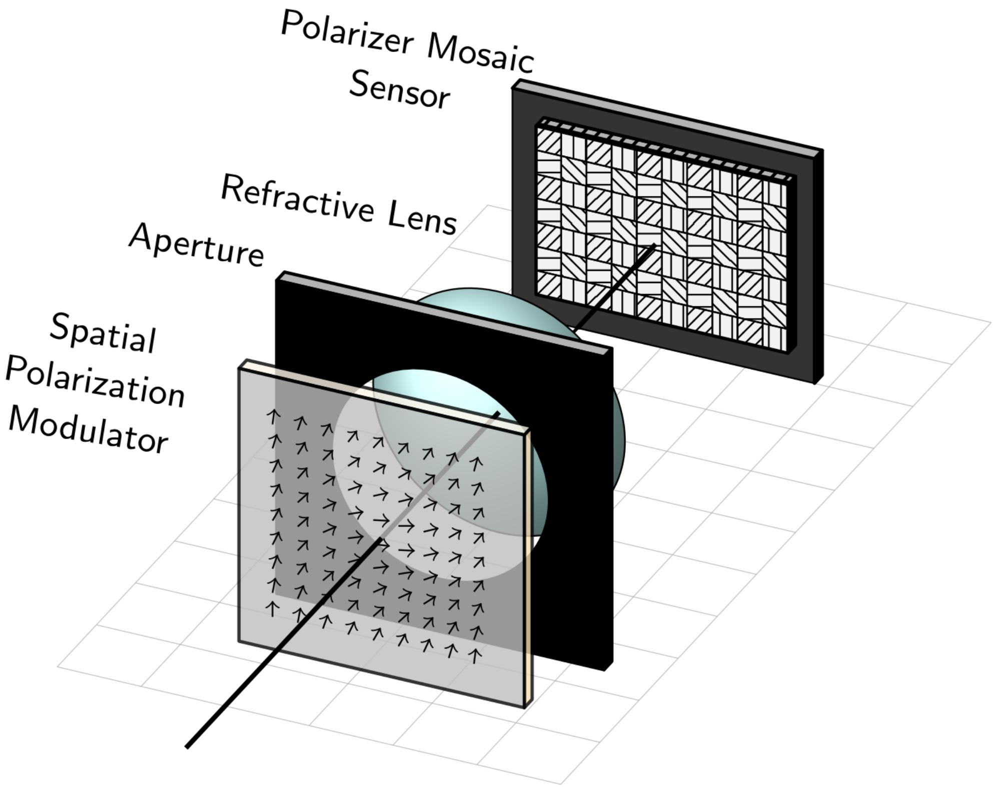


Formalize and understand this type of architecture

1. Can we use all four polarization channels for imaging?
2. What are the capabilities of this system?

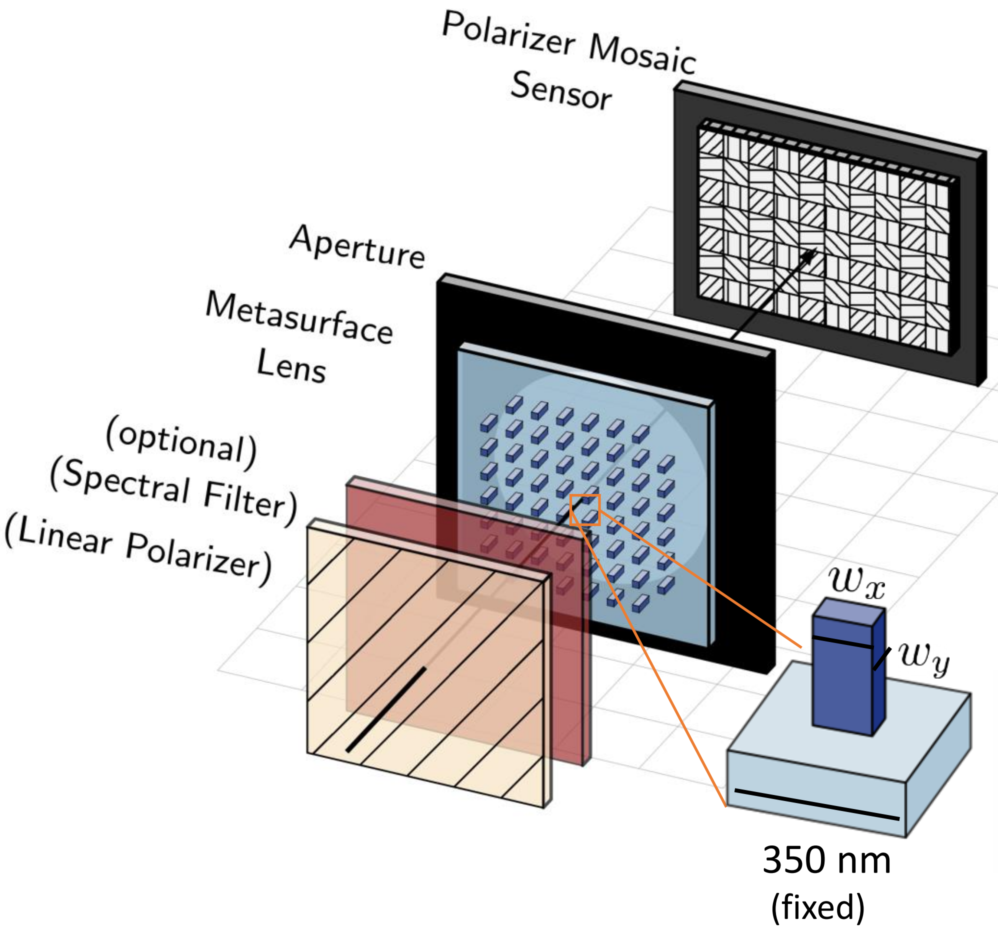
[2] B. Ghanekar et al., "Ps2 f: Polarized spiral point spread function for single-shot 3d sensing," ICCP 2022

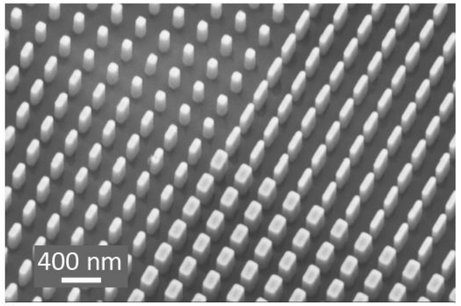
Snapshot **Polarization** Multi-Coded Imaging – New Opportunities



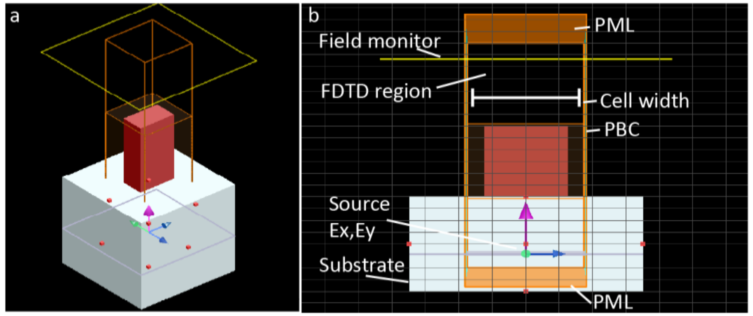
Creating the System with **Birefringent Metasurfaces**

Proposed metasurface-based architecture

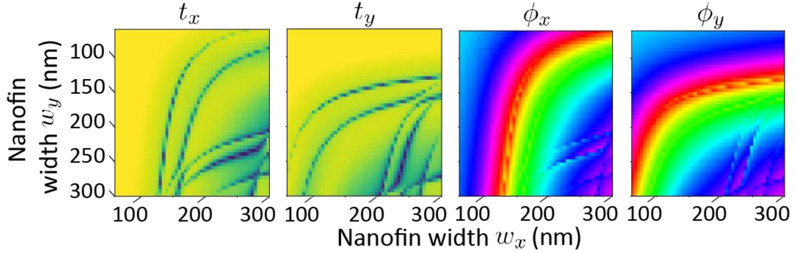




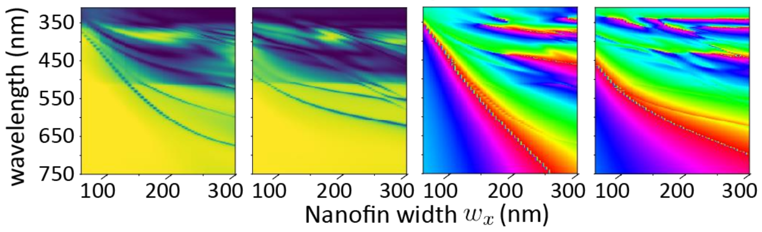
Cell design theory (review)



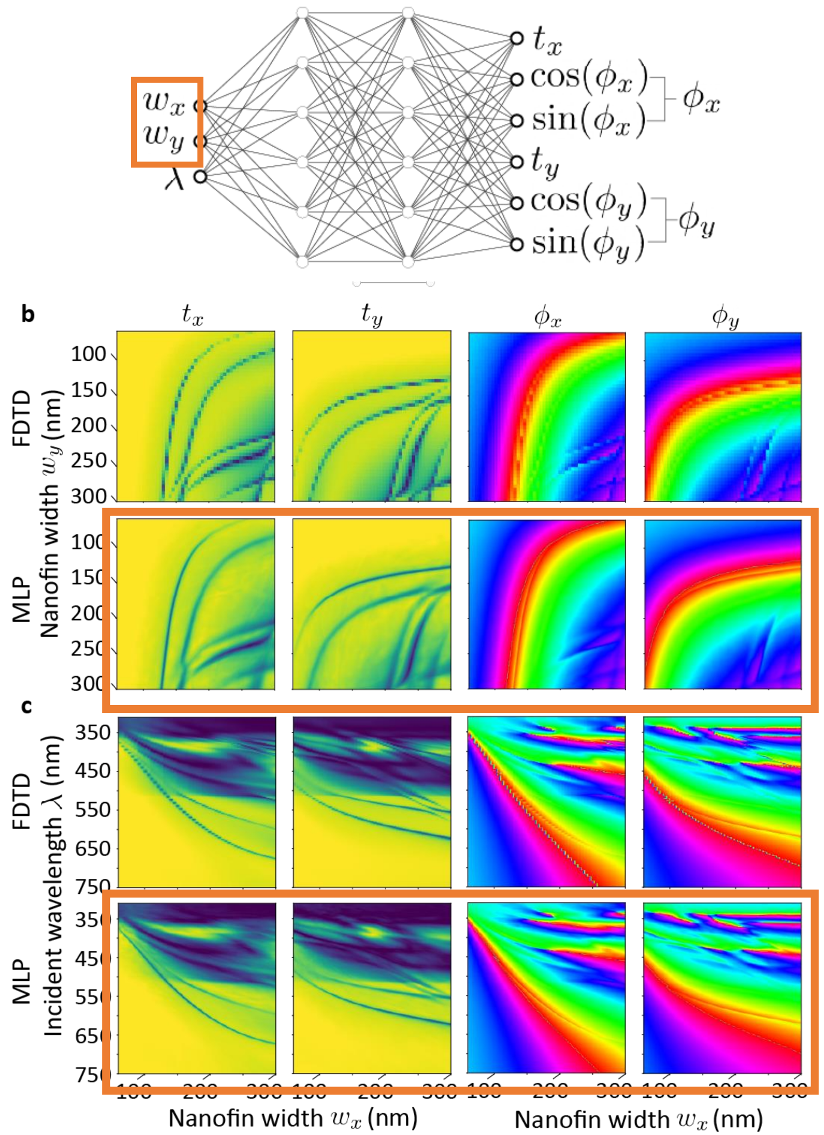
Fixed Wavelength (530 nm)

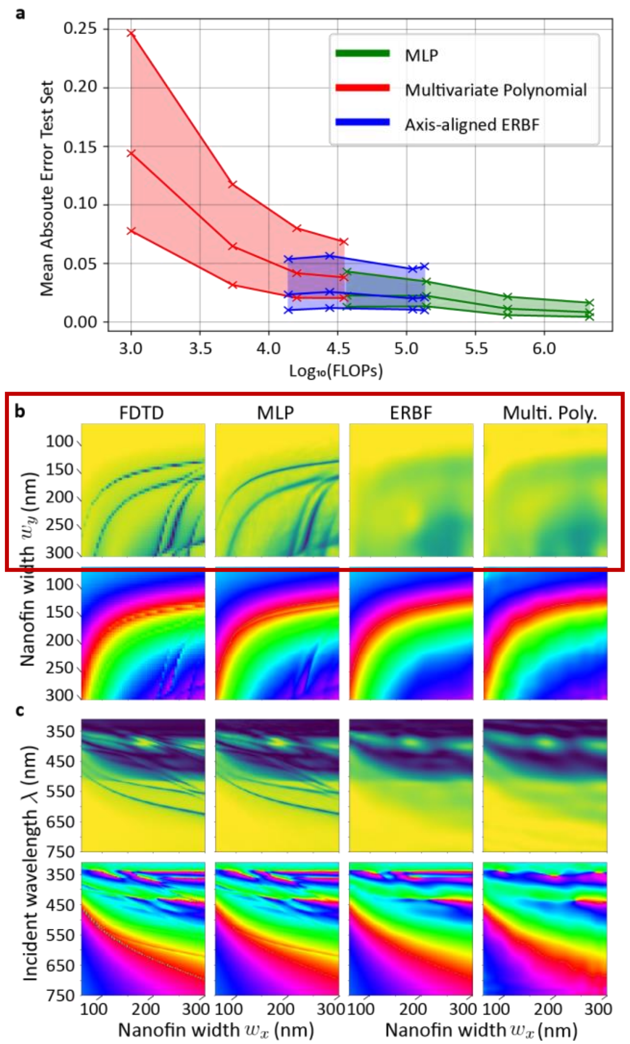


Fixed Width w_y =180 nm



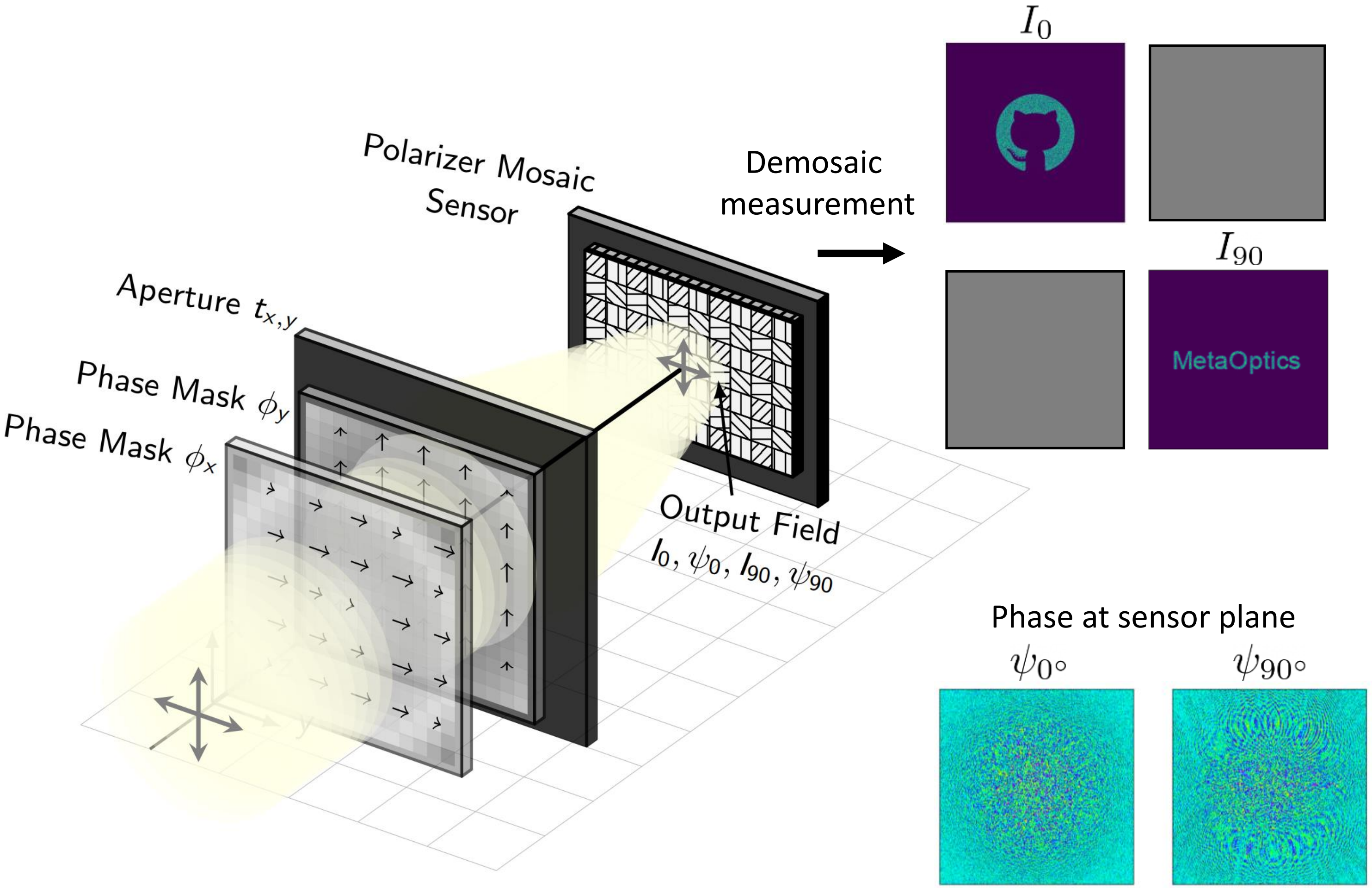
Neural Representation for Gradient Based Optimization





Fundamental Channel Capacity -- Interference of Polarized Light

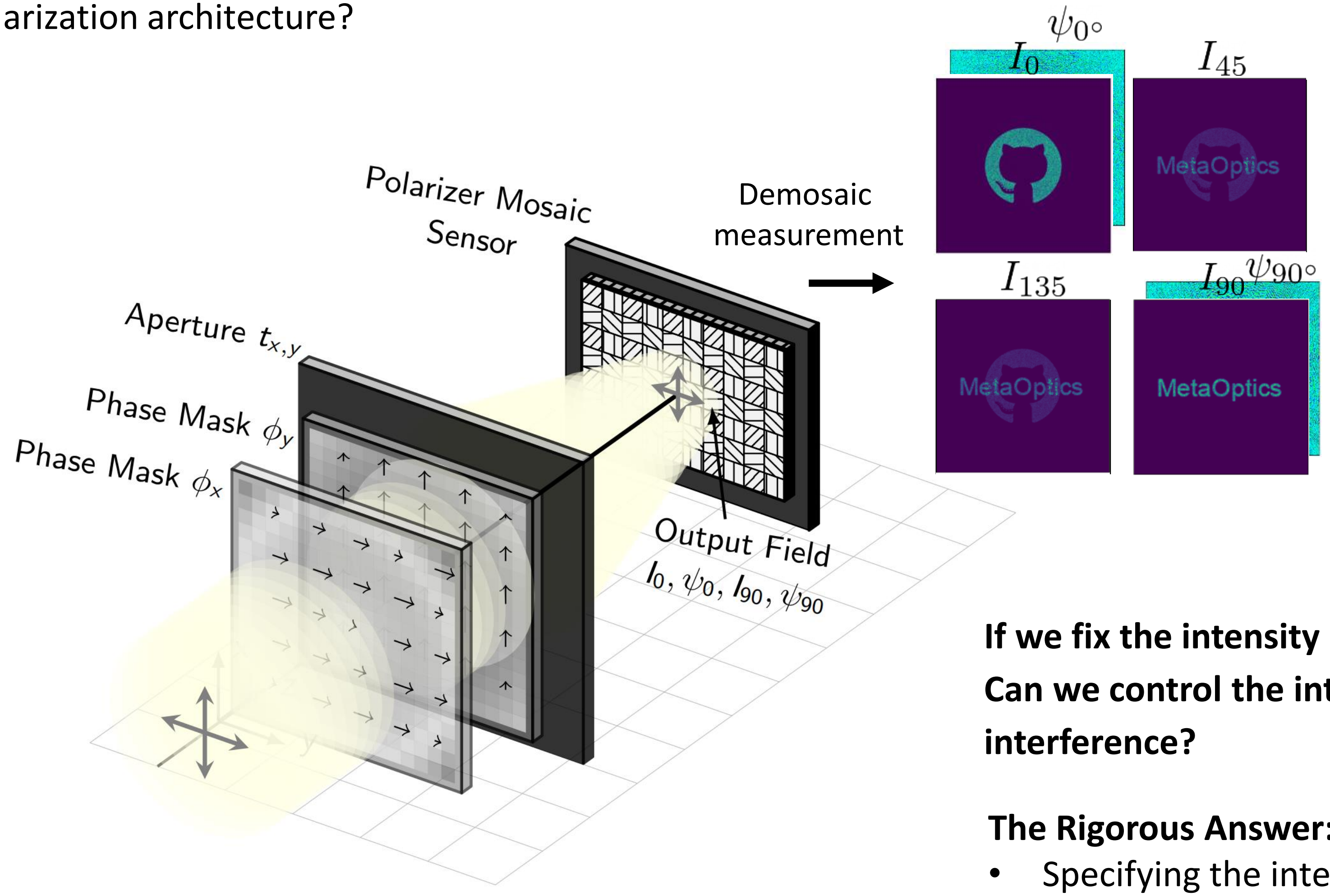
How many coded images can we design and measure with the polarization architecture?



Phase at sensor plane

Fundamental Channel Capacity -- Interference of Polarized Light

How many coded images can we design and measure with the polarization architecture?



$$I_{45,135} = \frac{I_0}{2} + \frac{I_{90}}{2} \pm \sqrt{I_0 I_{90}} \cos\left(\psi_0 - \psi_{90}\right)$$

If we fix the intensity distributions I_0, I_{90}…
Can we control the intensities I_{45}, I_{135} by optimizing the interference?

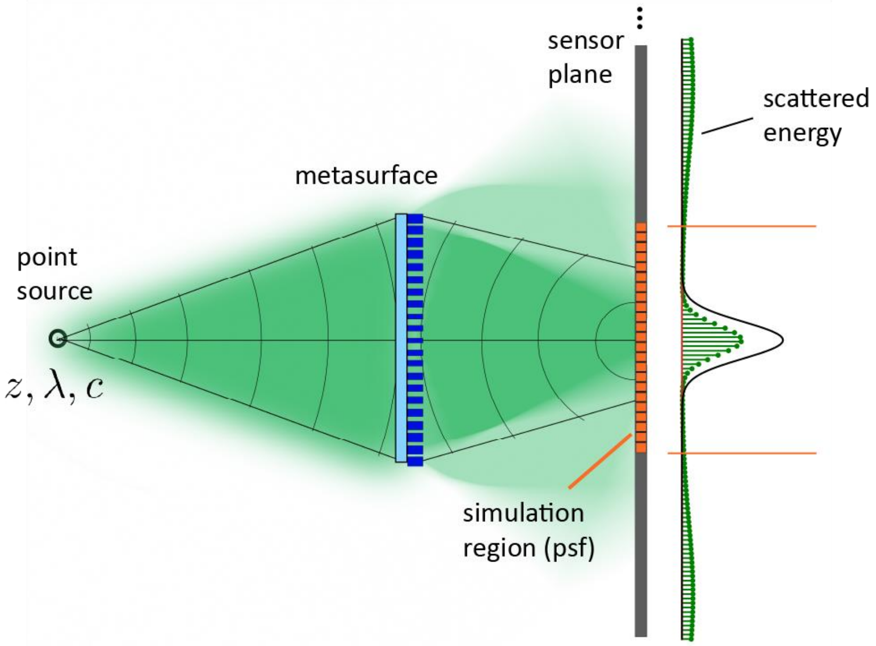
The Rigorous Answer: No…

- Specifying the intensity of light at the aperture and the sensor plane fixes its phase at both planes

Fundamental Channel Capacity -- Interference of Polarized Light

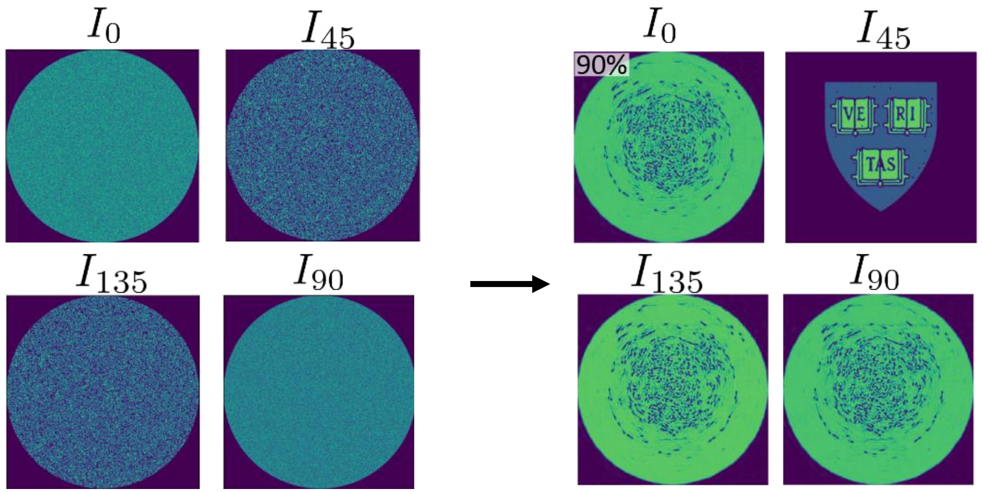
The Practical Answer: Yes… if we compromise

- I_0, I_{90}: There are an infinite number of possible intensity patterns that ***approximate*** the target distribution
- Each one of these solutions has a different output phase → they can produce a different interference effect



Different approximations:

- Scattering light outside simulation region
- Error in matching intensity within the region

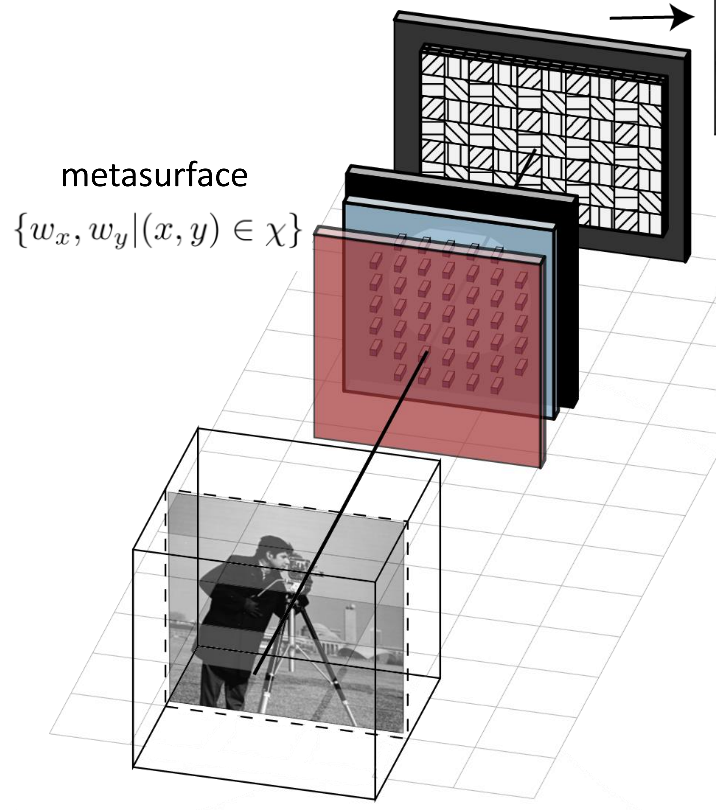


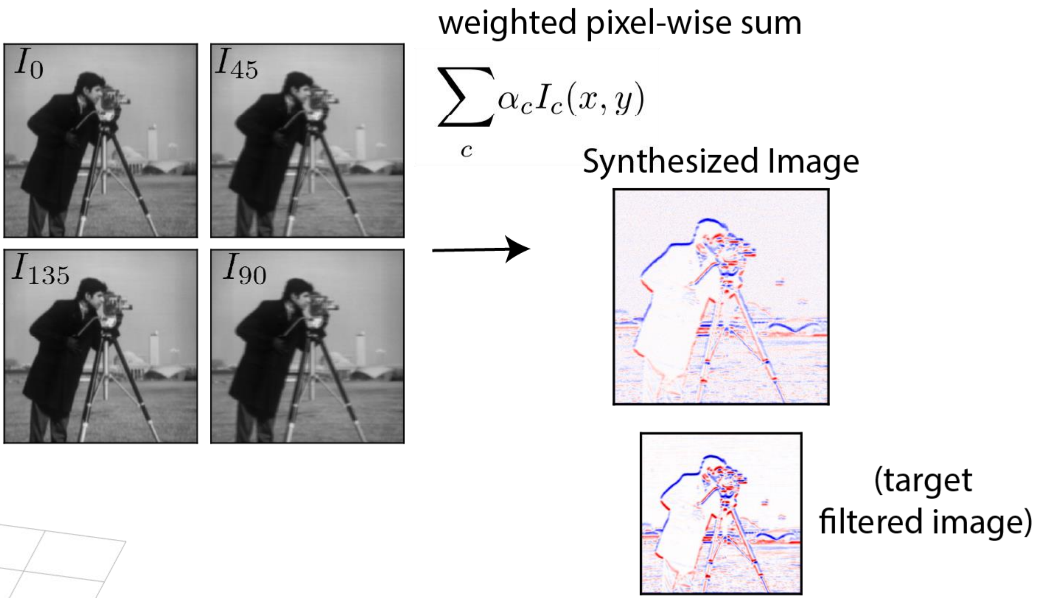
Minimum error intensity approximation to uniform disk I_0, I_{90}

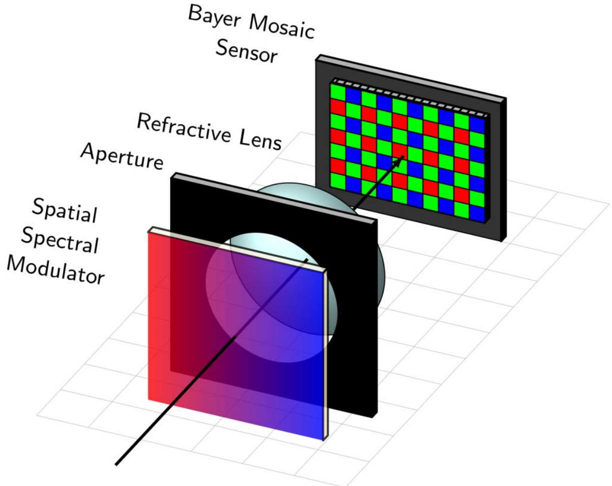
More error in intensity I_0, I_{90} to structure interference

In computational imaging, we generally care about codes that enable reconstruction vs exact patterns (end-to-end optimization)

Applying the System: **Multi-Image Synthesis** Problem







Only difference between the four images should be the point-spread function

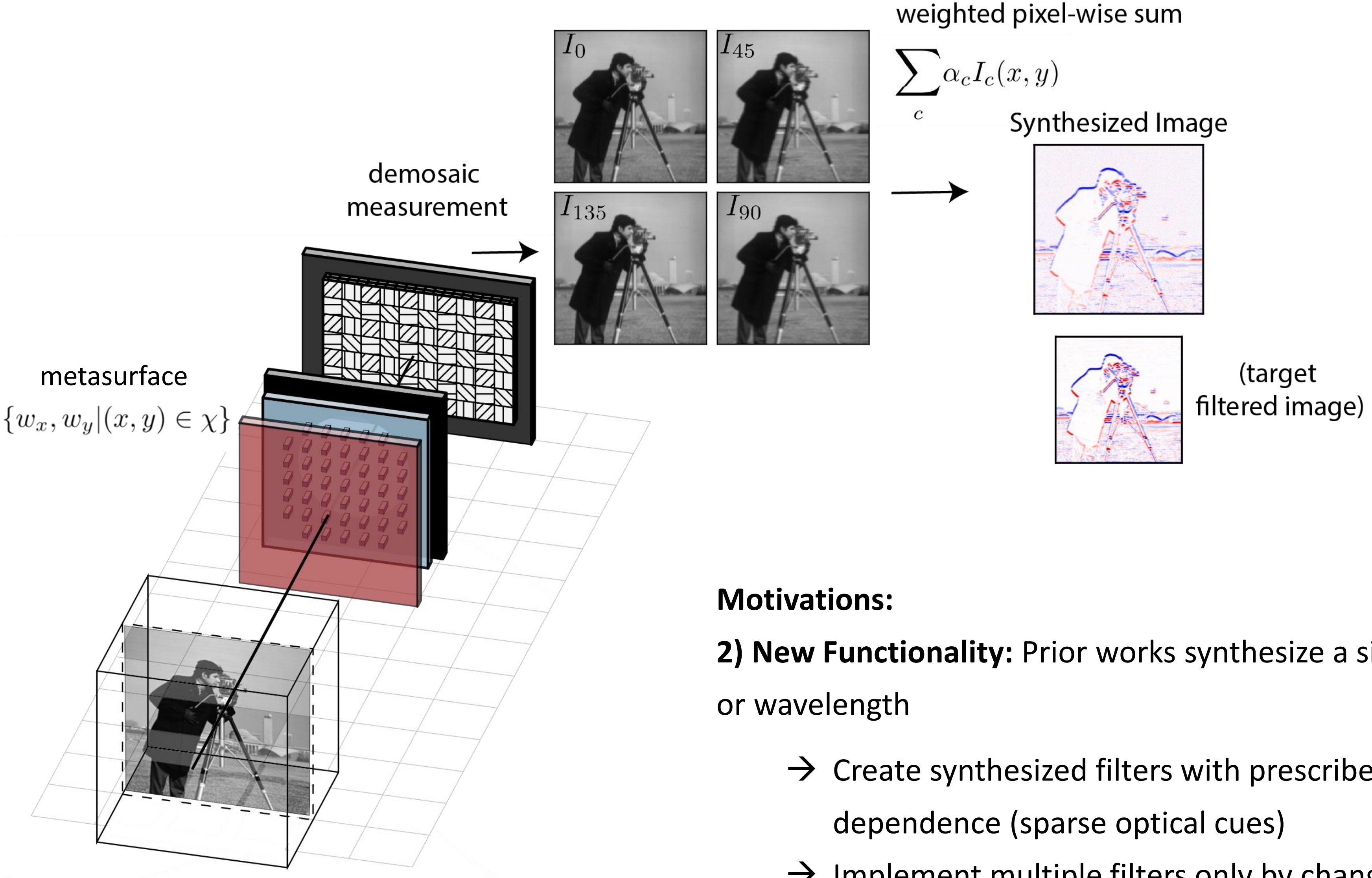
- Not true for spectral case

Motivations:

1) **Unsolved Hardware**: Compact and snapshot implementation of incoherent image processing for general scenes has not been achieved before

→ Problem cannot be solved with spectral coding and required transition to polarization

Applying the System: **Multi-Image Synthesis** Problem



weighted pixel-wise sum

$$\sum_c \alpha_c I_c(x,y)$$

Synthesized Image

demosaic measurement

metasurface

$\{w_x, w_y | (x,y) \in \chi\}$

(target filtered image)

Motivations:

2) New Functionality: Prior works synthesize a single optical filter for single depth or wavelength

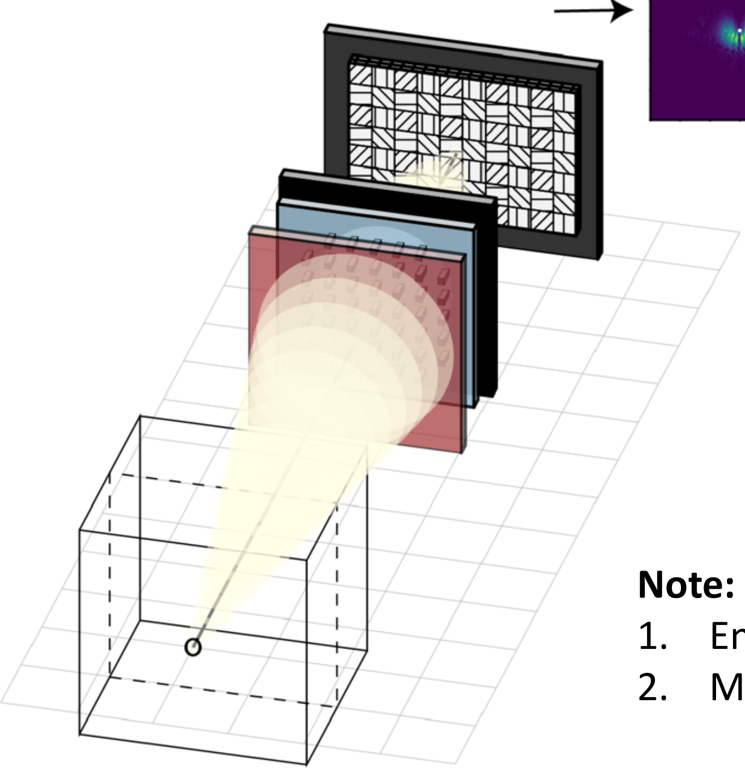
→ Create synthesized filters with prescribed depth or wavelength dependence (sparse optical cues)

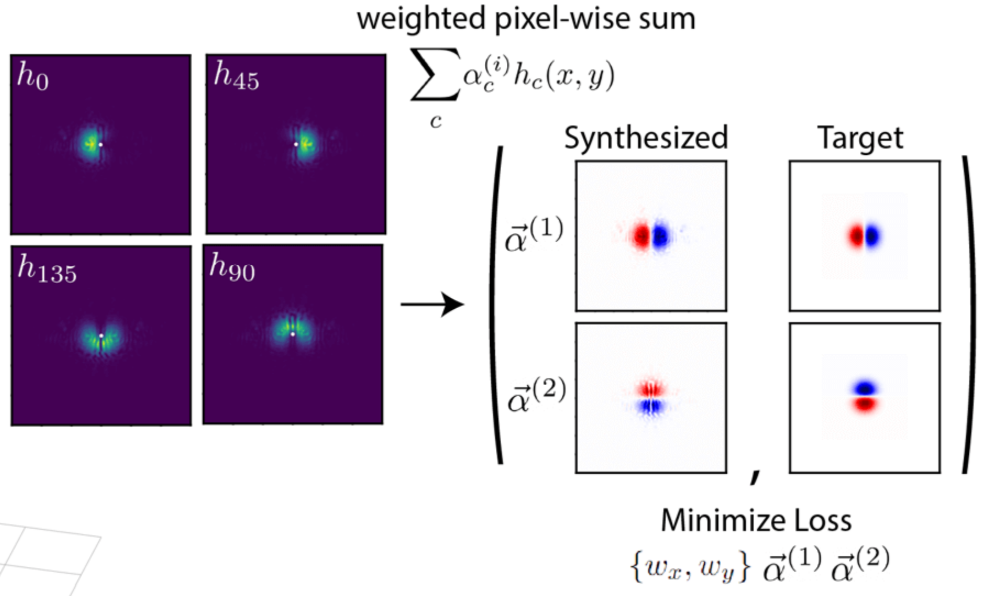
→ Implement multiple filters only by changing the summation weights

Multiple Filtered Images from a Single Exposure

Task: Achieve different filtering operations only by changing the digital summation weights

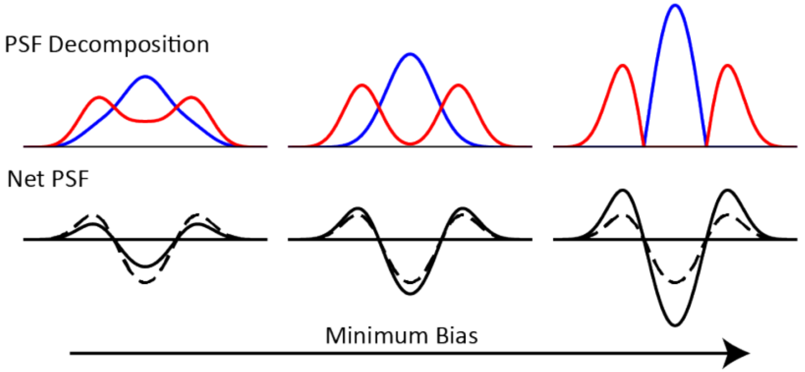
Minimize loss based on the point-spread function (PSF)





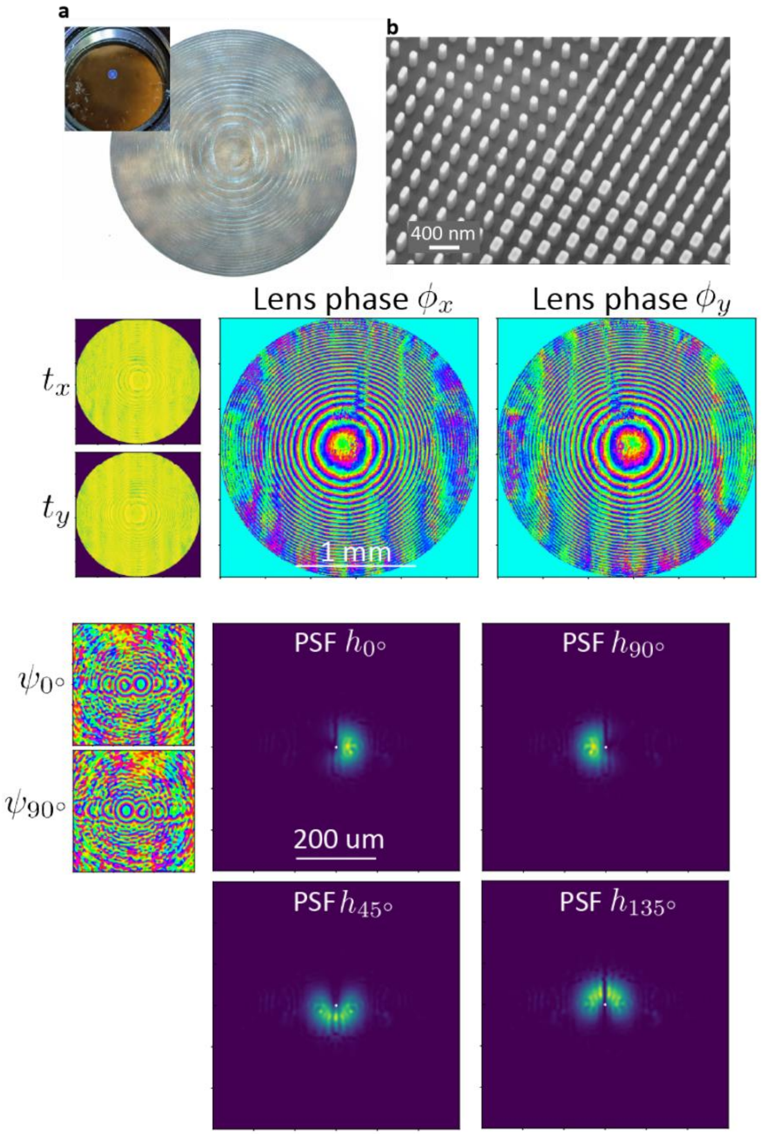
Note: Regularization is Crucial!

1. Enforce light efficiency
2. Minimum Bias Factorizations

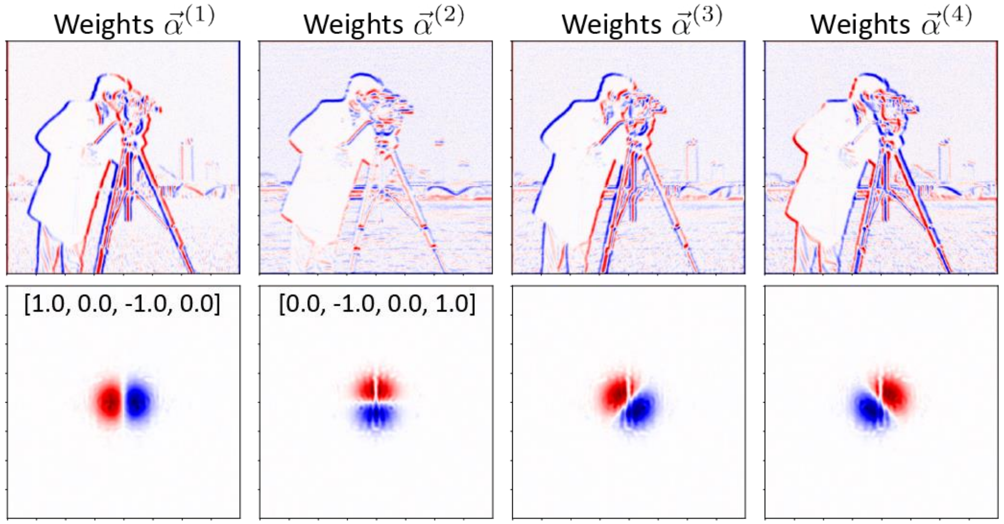


Multiple Filtered Images from a Single Exposure

Steerable Gaussian Derivatives



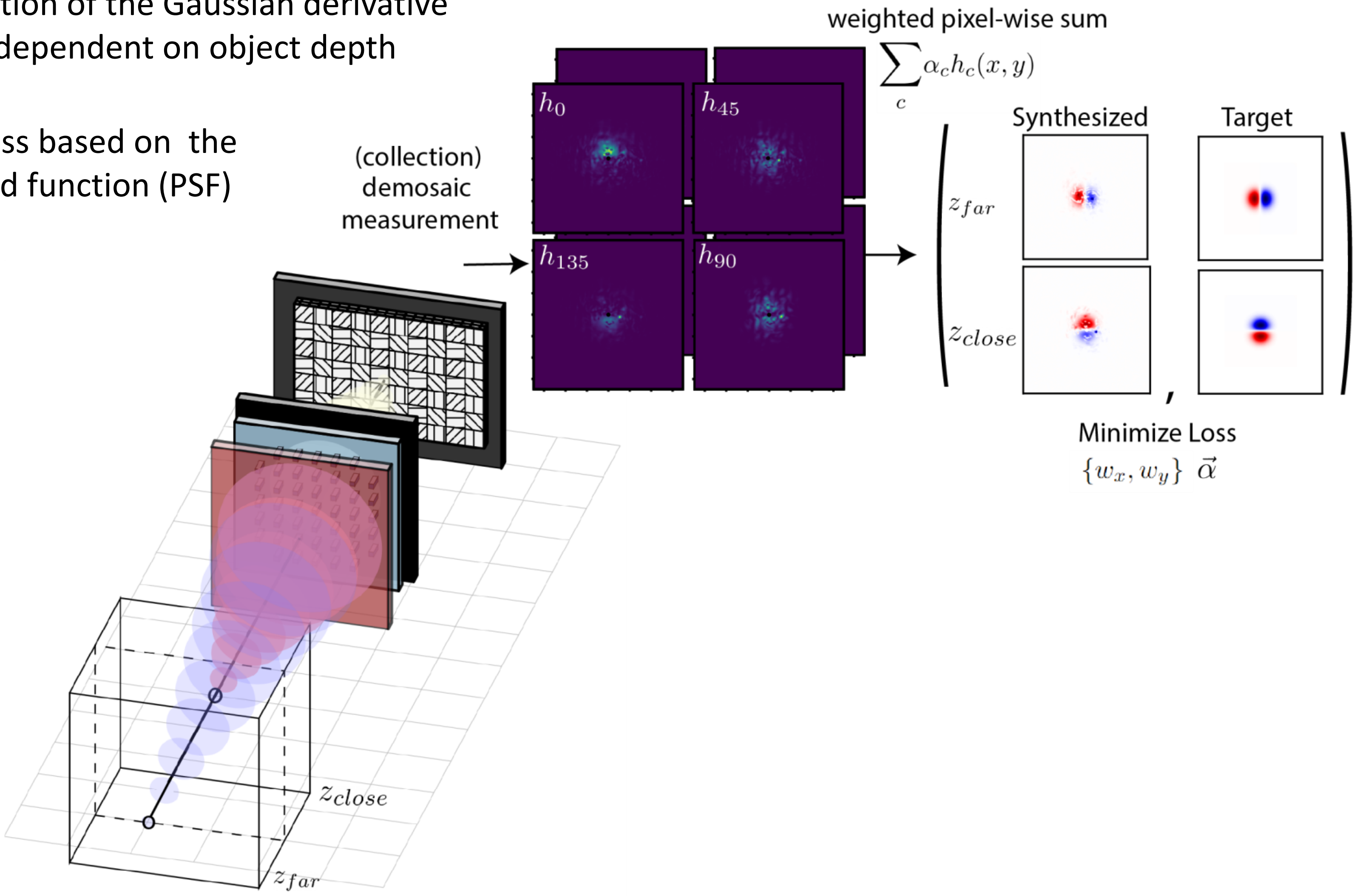
By changing the summation weights used to combine the four captured images, we can obtain the derivative along any orientation – *at an absolute minimum computational cost*



Depth Dependent Derivatives

Task: Orientation of the Gaussian derivative kernel to be dependent on object depth

Minimize loss based on the point-spread function (PSF)



(collection) demosaic measurement

weighted pixel-wise sum

$\sum_c \alpha_c h_c(x, y)$

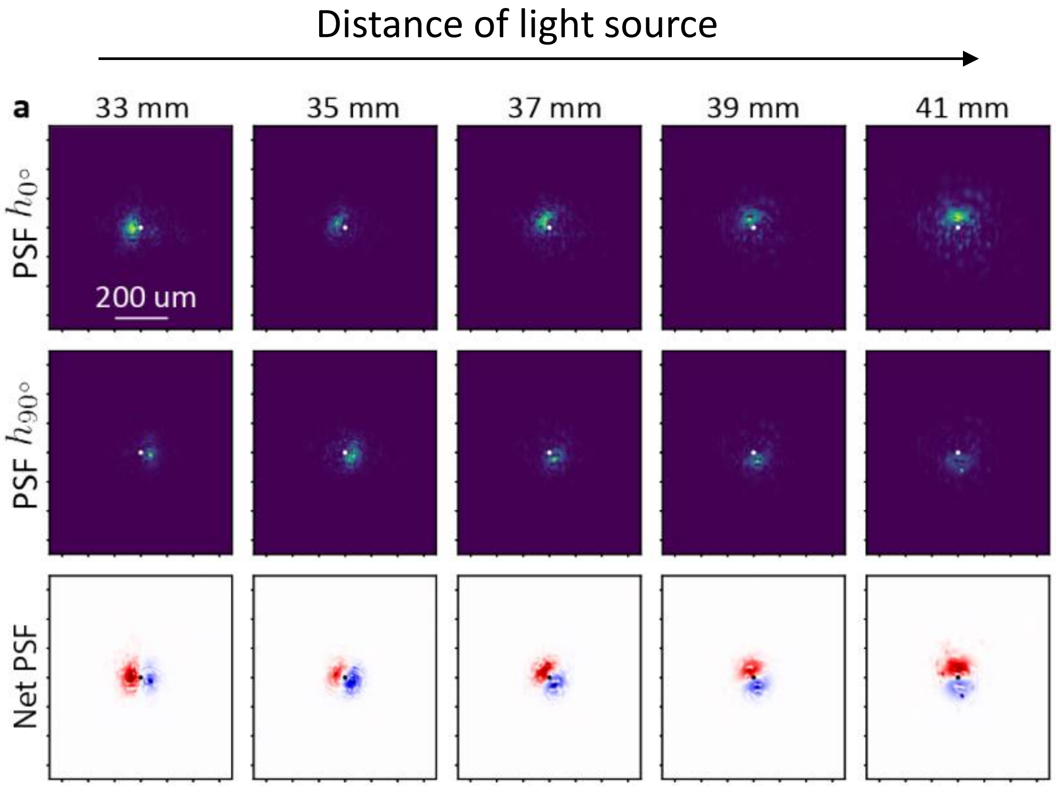
Synthesized

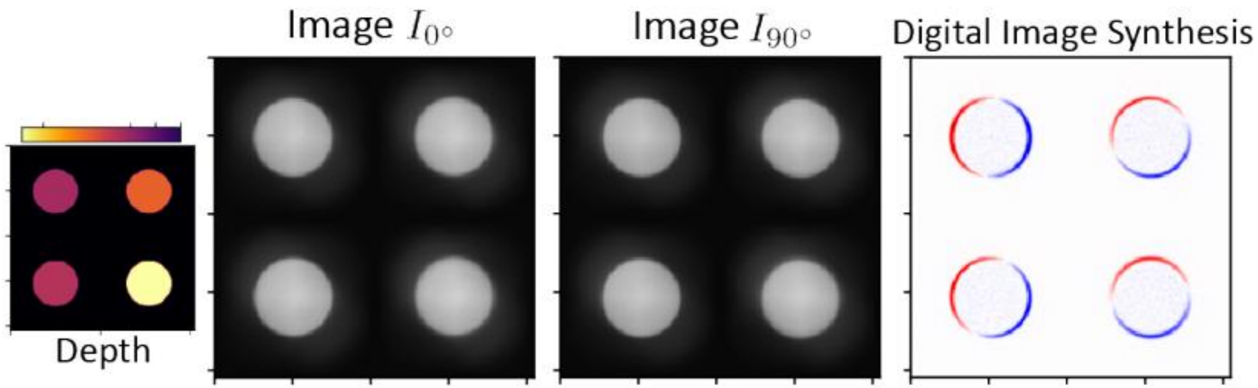
Target

Minimize Loss

$\{w_x, w_y\}$ $\vec{\alpha}$

Depth Dependent Derivatives





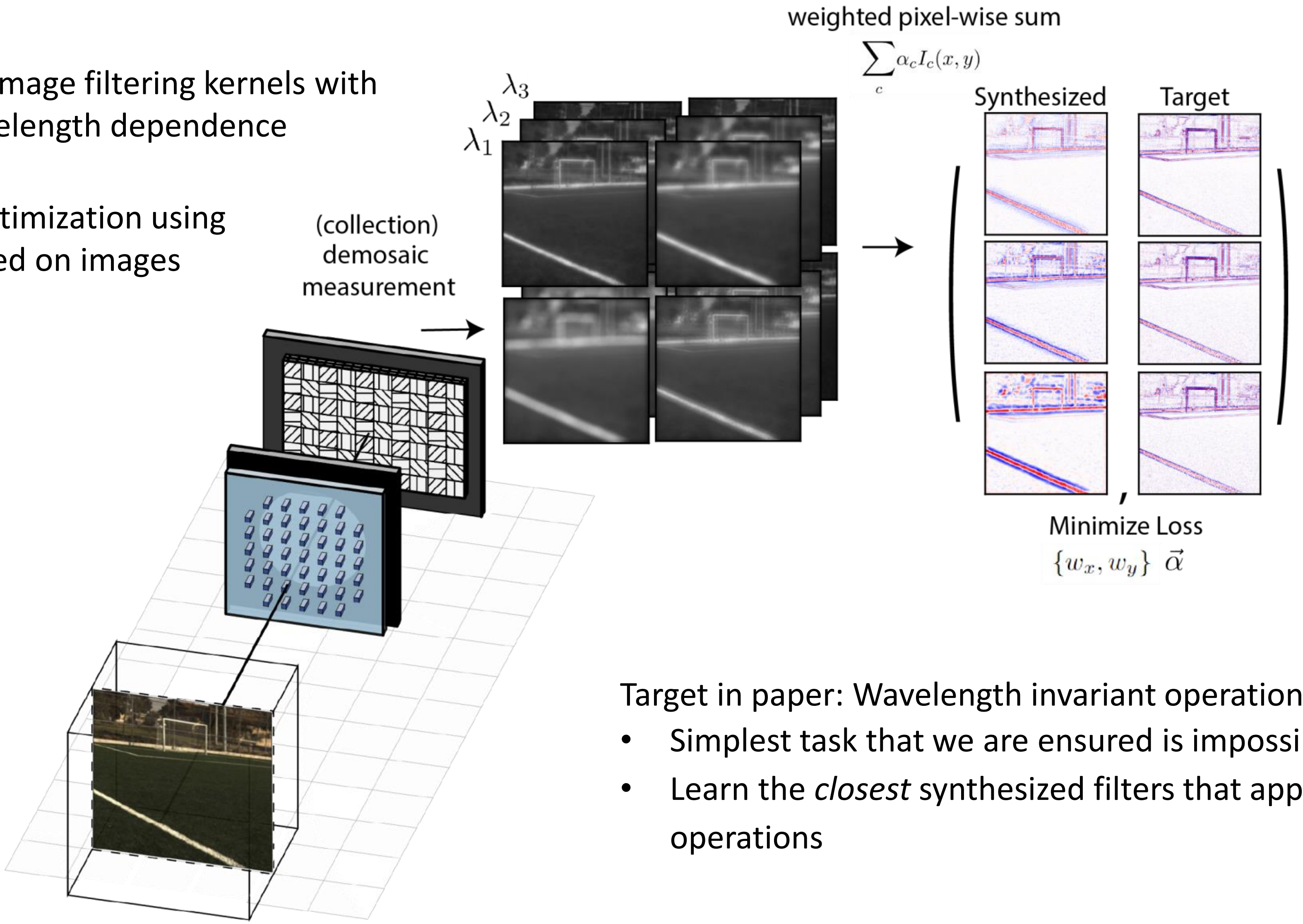
Different regions of the image have a different spatial frequency filter applied to it dependent on the depth map

- Synthesis requires only 3 FLOPs
- Difficult to produce equivalent image purely digitally

Engineering Synthesized Filters with Respect to Wavelength

Task: Synthesize image filtering kernels with a prescribed wavelength dependence

End-to-end optimization using a loss computed on images

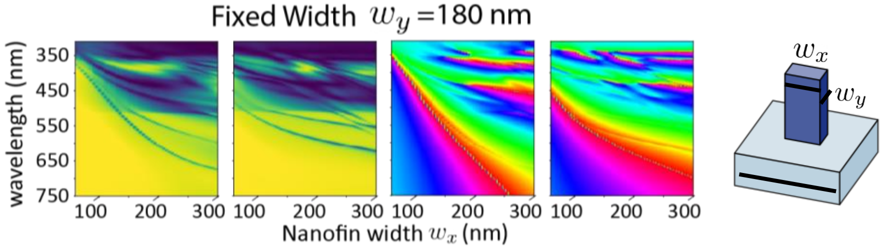


Target in paper: Wavelength invariant operation

- Simplest task that we are ensured is impossible to realize exactly
- Learn the *closest* synthesized filters that approximate our target operations

Engineering Synthesized Filters with Respect to Wavelength

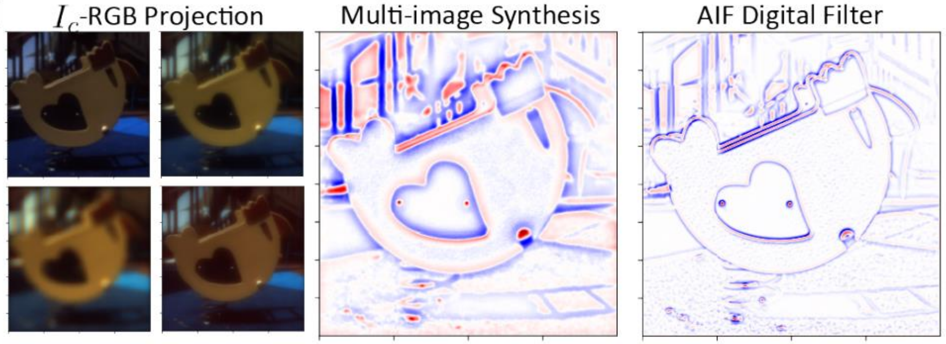
Metasurfaces are dispersive



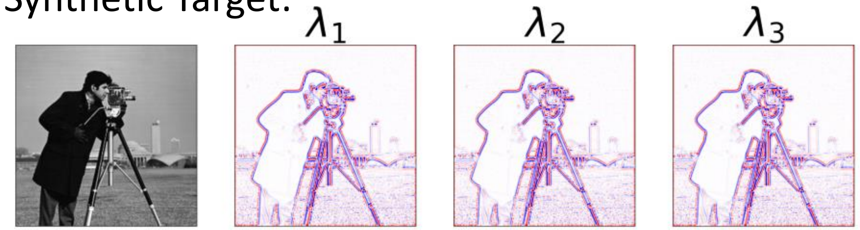
Each nanostructure has a different wavelength dependent phase

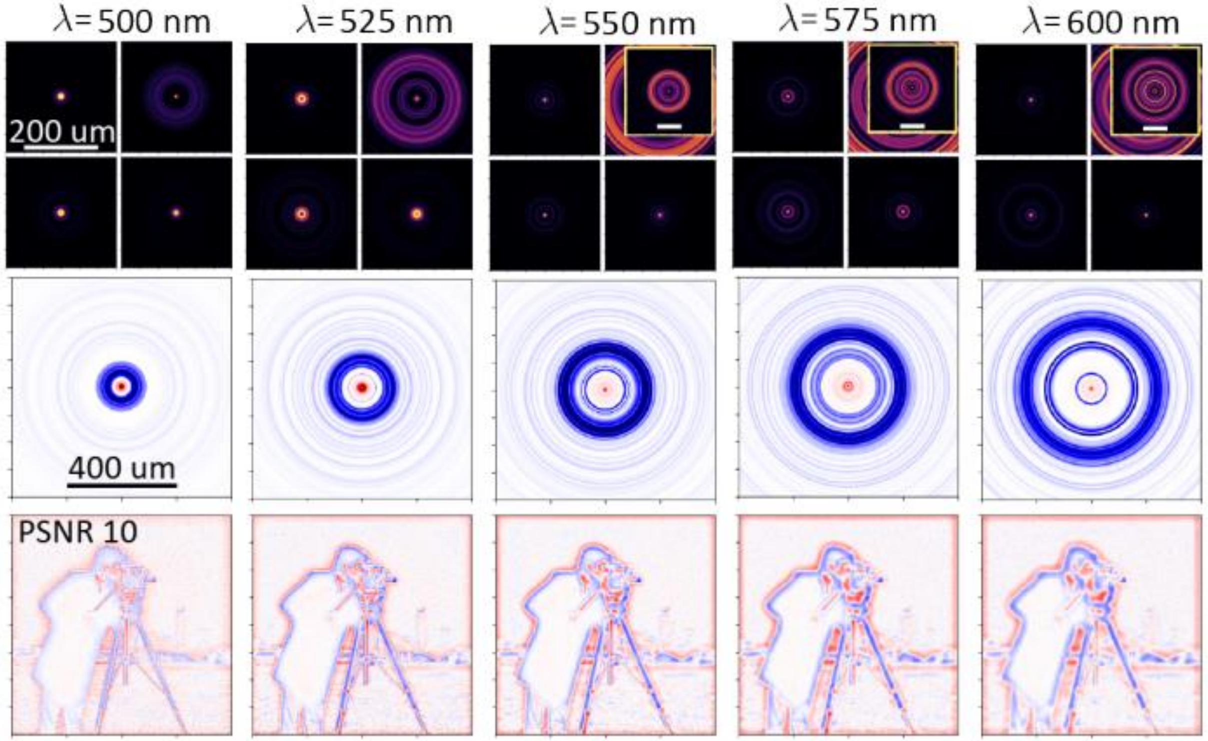
→ Ability to optimize and control the set of PSFs with respect to wavelength

Zero-Shot Generalization (Arad1k dataset)

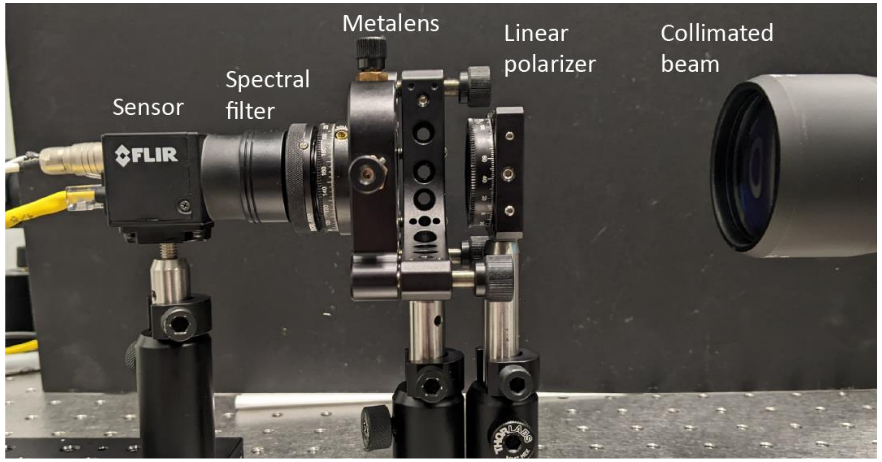


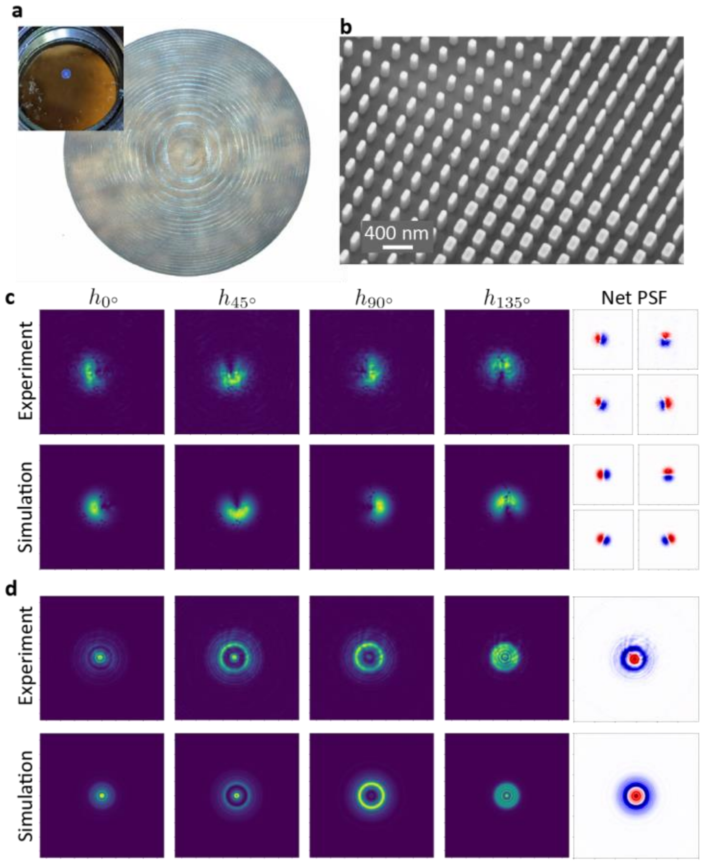
Synthetic Target:

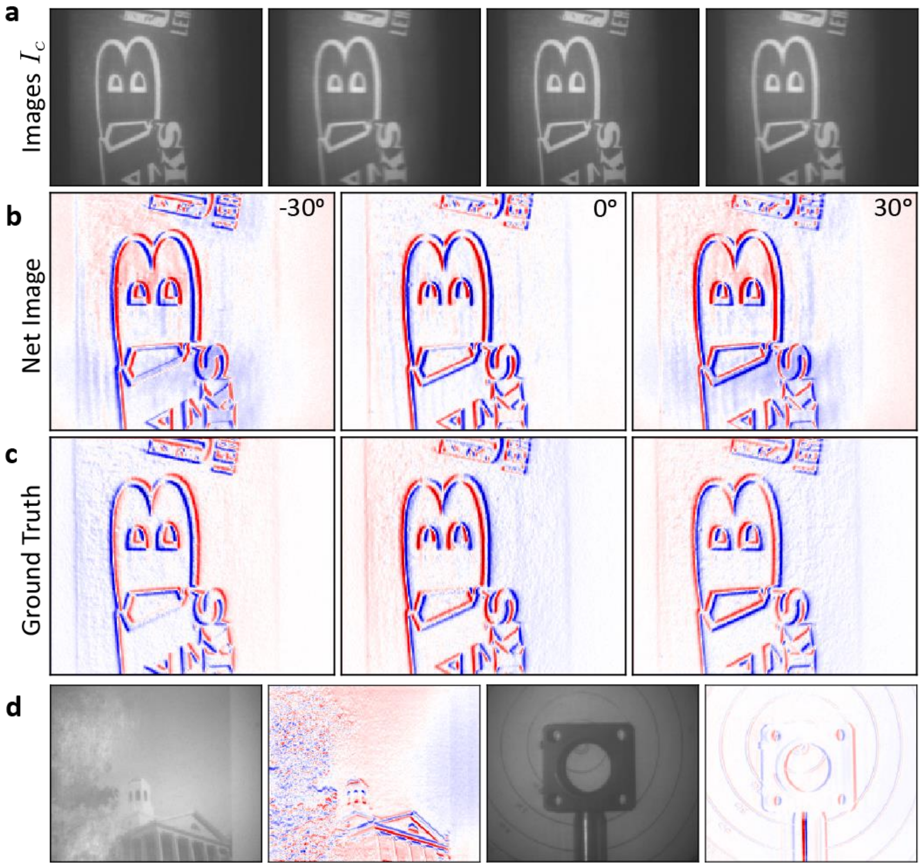




Validation of Design Theory with Prototype Camera







- Metasurface
- Off-the-shelf polarizer-mosaiced sensor
- (Linear polarizer if we can’t assume unpolarized light)
- (Spectral filter if we are testing single wavelength)

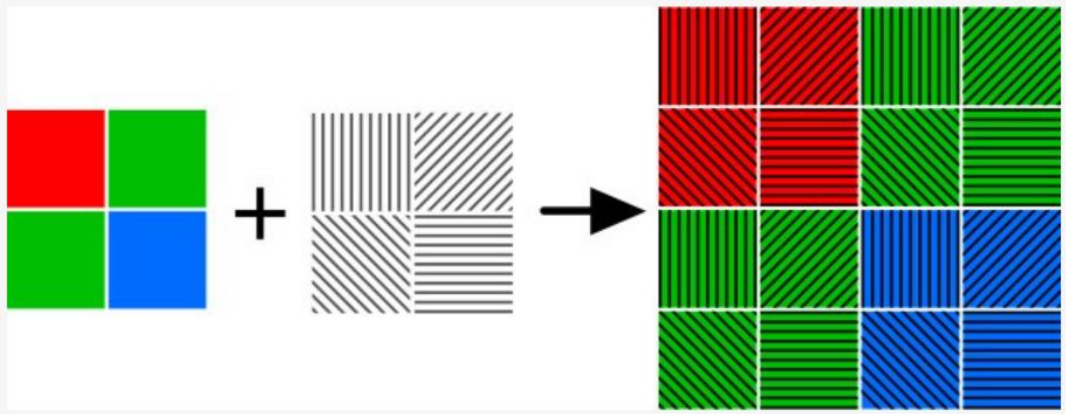
Conclusions and Future Remarks

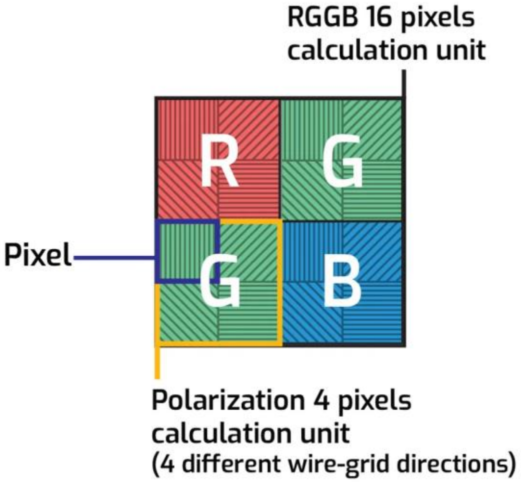
Take-Aways:

- Metasurfaces excel at polarization (and wavelength) transformations
- Polarization, like wavelength, can be used as distinct multiplexed imaging channels
- Metasurfaces designed for multi-coded imaging can minimize/reduce computational costs

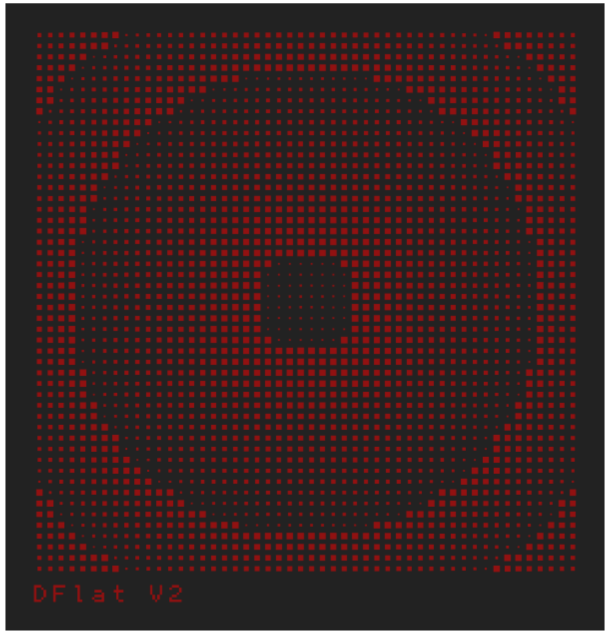
Future Remarks: Polarization and Spectral multi-coded systems are not mutually exclusive!

- Future systems can combine the two (metasurface is still ideal)
- Limitation of spatial resolution → Improved by smart demosaicing using learned statistical priors
- **Optimize the capture of 16 distinctly coded images in a single snapshot**





Thanks for listening



Open-source Auto-differentiable design framework (Tensorflow, Pytorch)

- Share metasurface cell libraries
- Pre-trained implicit Representations (MLP, ERBF, Multivariate-Poly)
- Field Propagation (Hankel + FFT; Angular Spectrum, Fresnel, Exact)
- Scene rendering operations (convolutional, noise)
- field solver (RCWA)

Special Thanks:

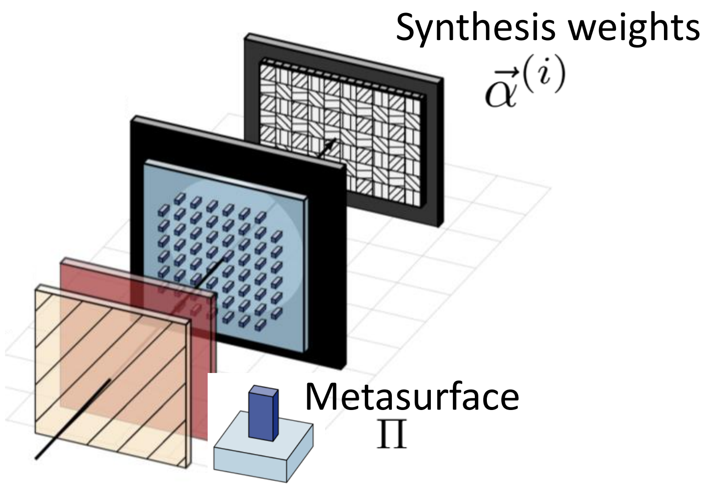
Mia Polansky

Aneel Damaraju

Dr. Zhujun Shi

Supplemental Slides

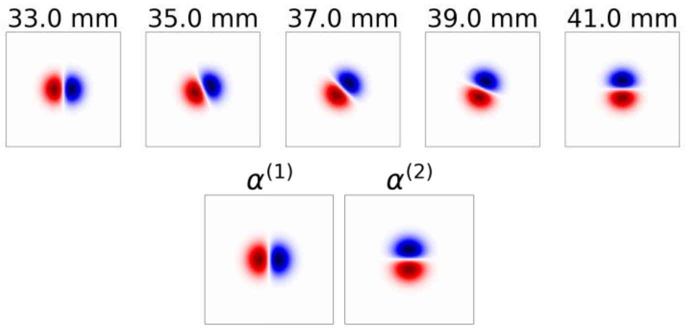
Gradient Descent With Regularization

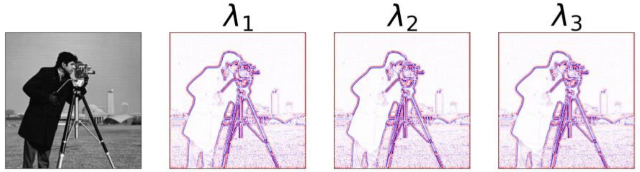


PSF decomposition as a constrained, non-negative matrix factorization problem:

$$\underset{H\geq 0, A}{\operatorname{argmin}} \left\| F - HA \right\|^2$$

- The set of four PSFs (columns of H) are parameterized by metasurface Π
- Additional coupling by interference between different polarization channels
- Not all factorizations are equally useful in the presence of noise!





Filter-Target Objective

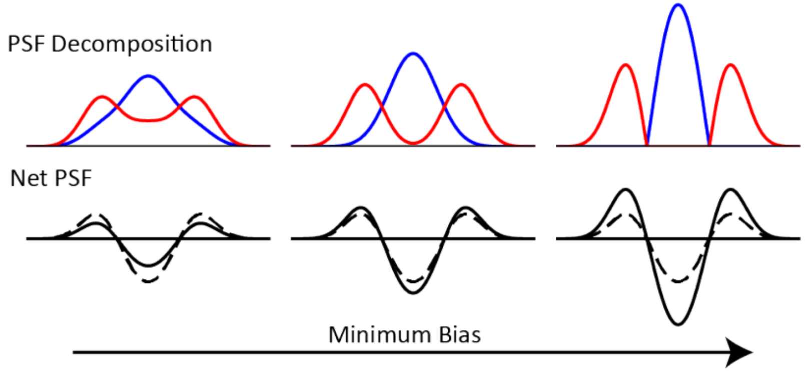
$$\underset{\alpha,\Pi}{\operatorname{argmin}} \sum_i \left[\left\| \frac{F^{(i)}}{\left\| F^{(i)} \right\|_2} - \frac{H\alpha^{(i)}}{\left\| H\alpha^{(i)} \right\|_2} \right\| + \mathcal{R} \right]$$

Image-Target Objective

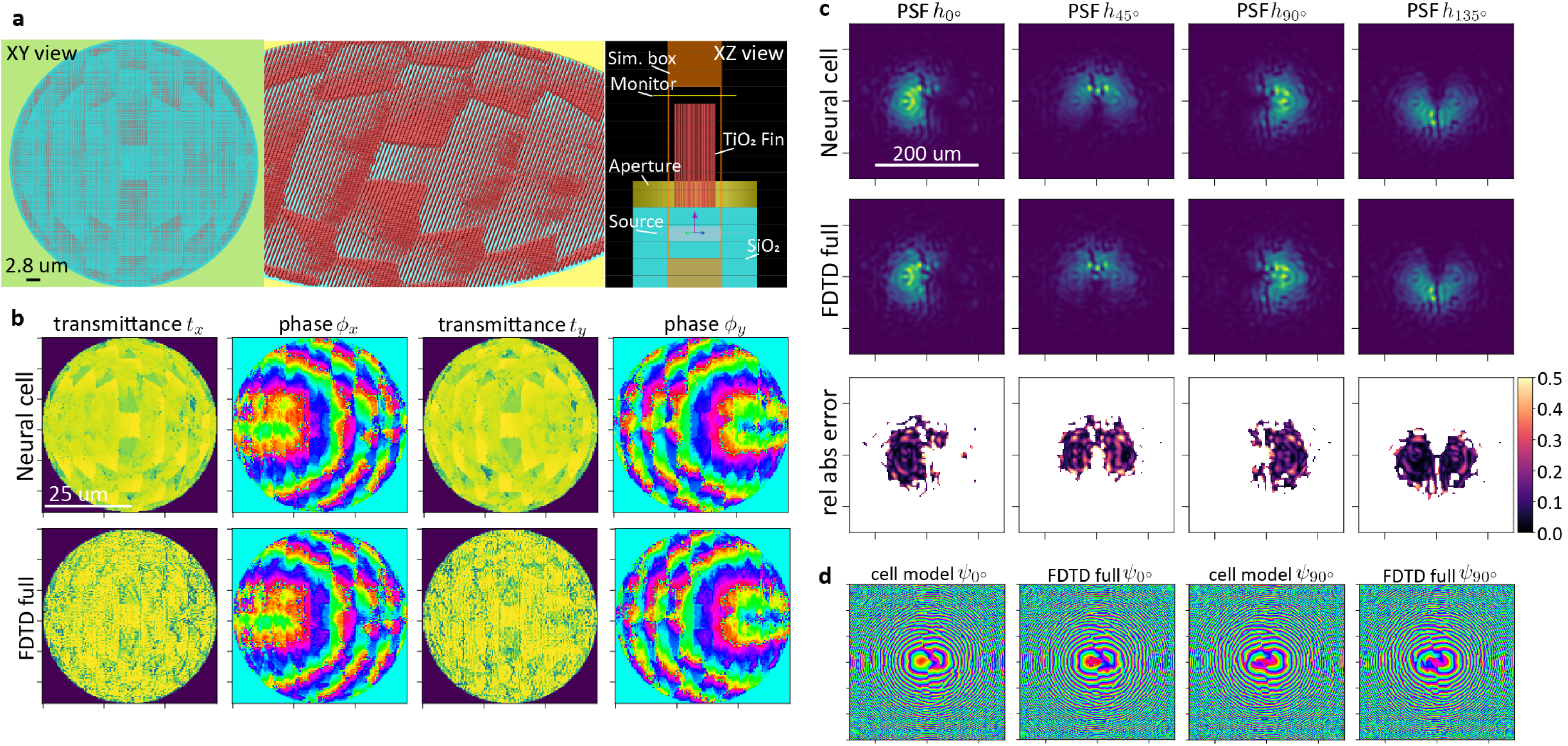
$$\underset{\alpha,\Pi}{\operatorname{argmin}} \sum_i \left[\left\| \frac{F^{(i)} * \mathcal{I}}{\left\| F^{(i)} \right\|_2} - \frac{(H * \mathcal{I})\alpha^{(i)}}{\left\| H\alpha^{(i)} \right\|_2} \right\| + \mathcal{R} \right]$$

Regularizer $\mathcal{R}$:

1. Enforce light efficiency & the PSFs to be spatial compact
2. Minimum Bias Factorizations



Validation of the Cell Design Principle with Full Lens FDTD Simulations



Slide Variants