High resolution holographic image synthesis for future display eyeglasses

Praneeth Chakravarthula

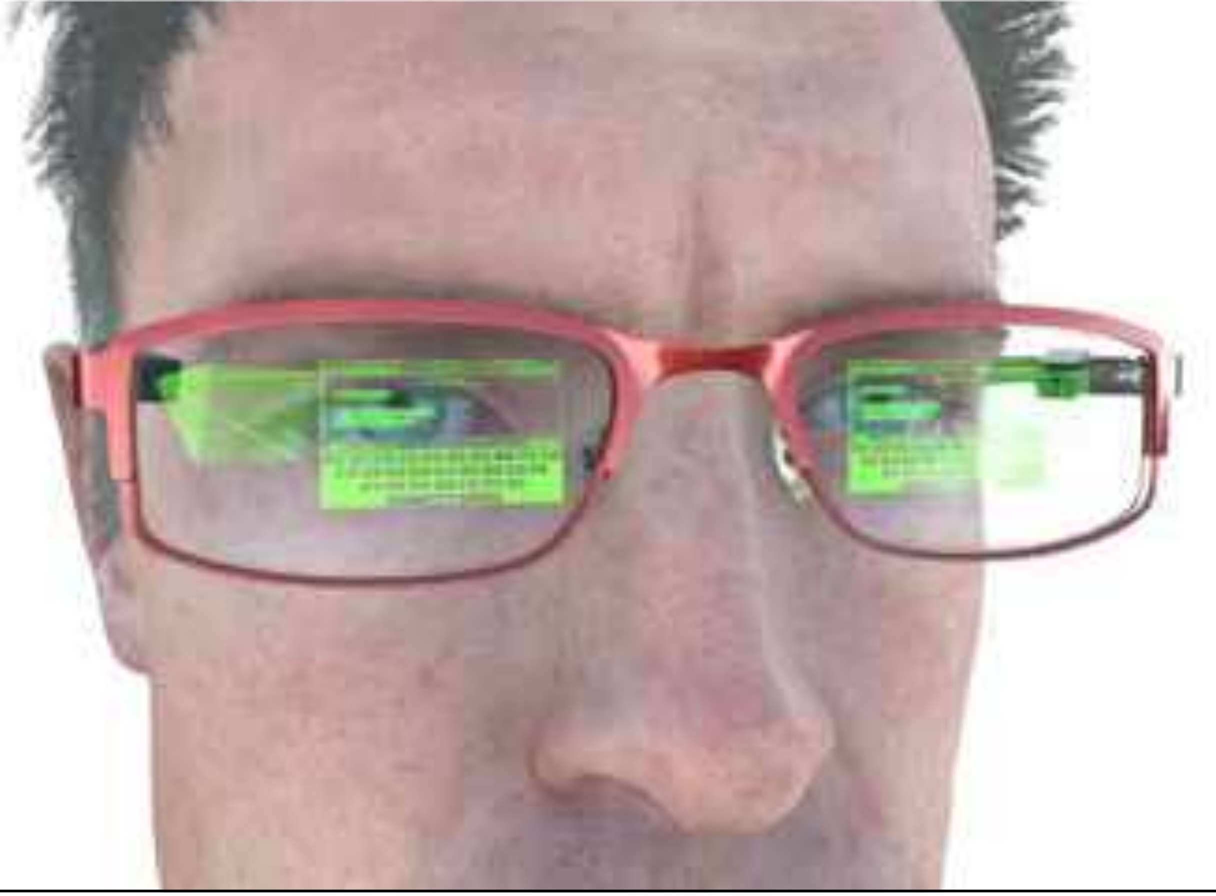
UNC Chapel Hill

Eyeglasses-Style Near-Eye Display Optics

Wide field of view

High resolution

Accommodation support



Eyeglasses-Style Near-Eye Display Optics

Wide field of view

Moderate resolution

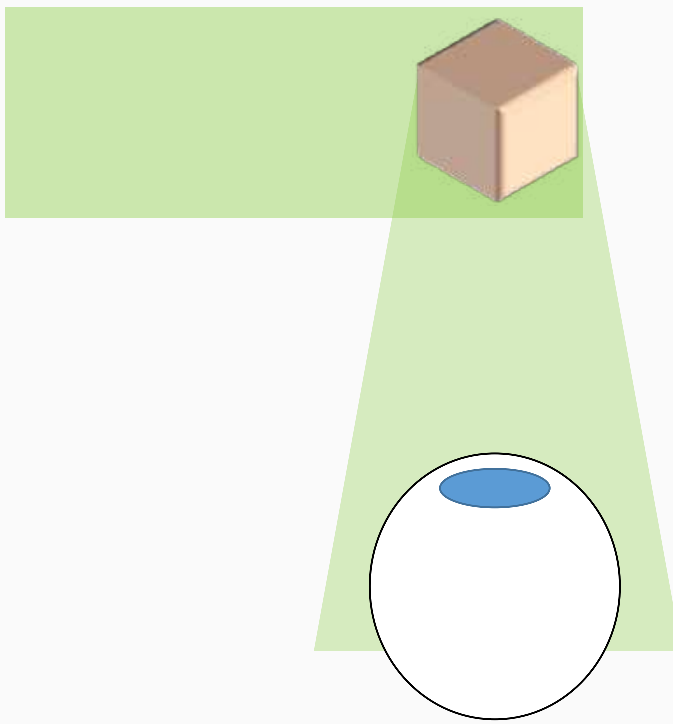
Accommodation support

Holography is the only demonstrated technology for getting everything

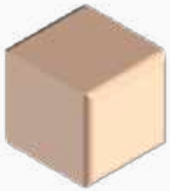
Maimone et al. 2017

Basics of Digital Holography

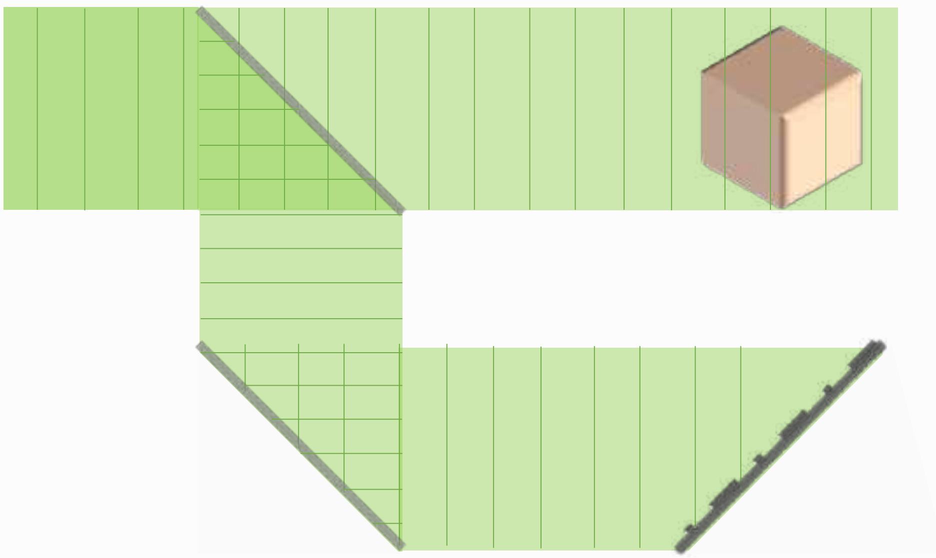
Principle of Holography



Principle of Holography

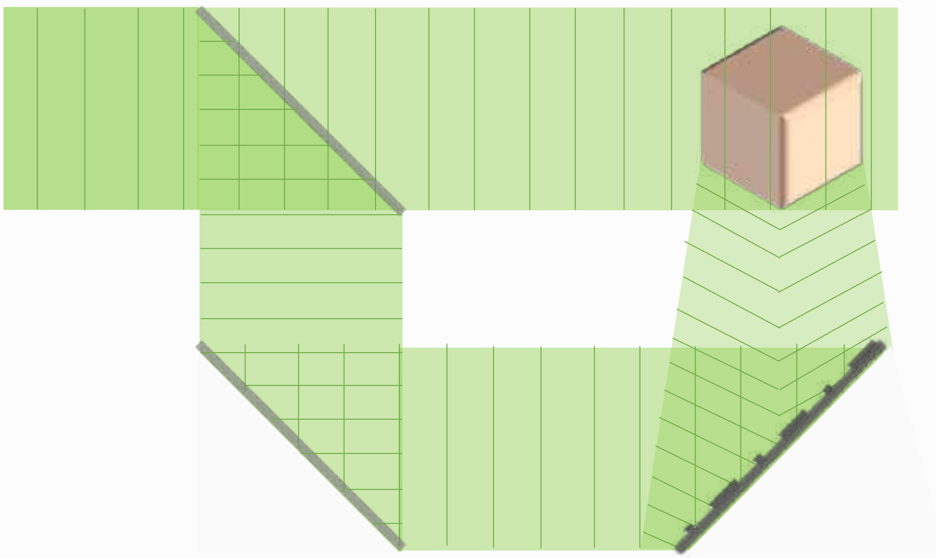


Principle of Holography



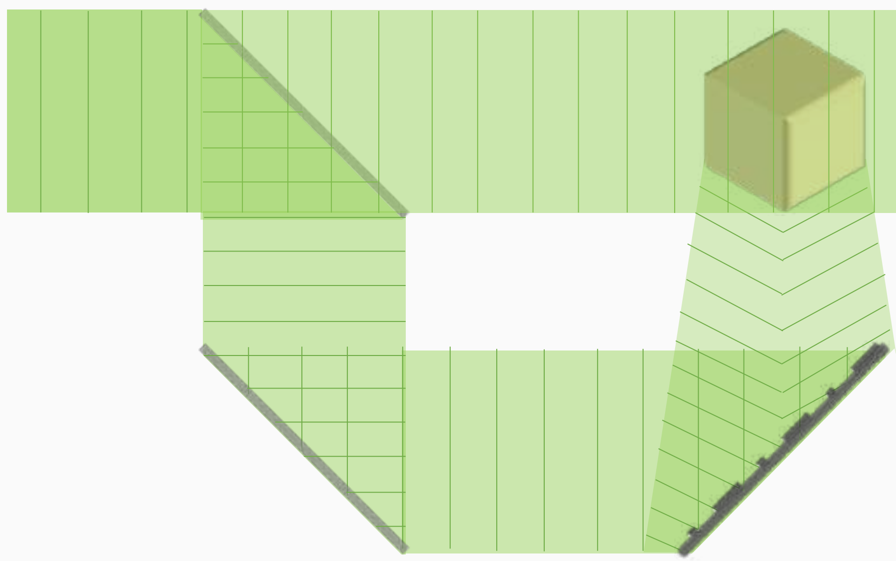
Step 1: Recording

Principle of Holography



Step 1: Recording

Principle of Holography



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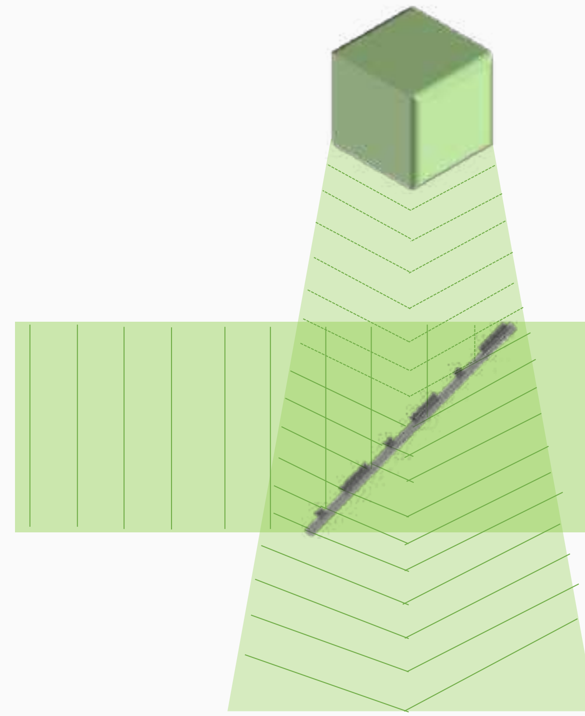
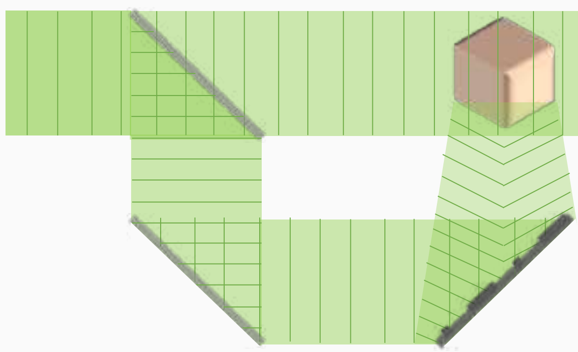


Step 2: Playback

Principle of Holography



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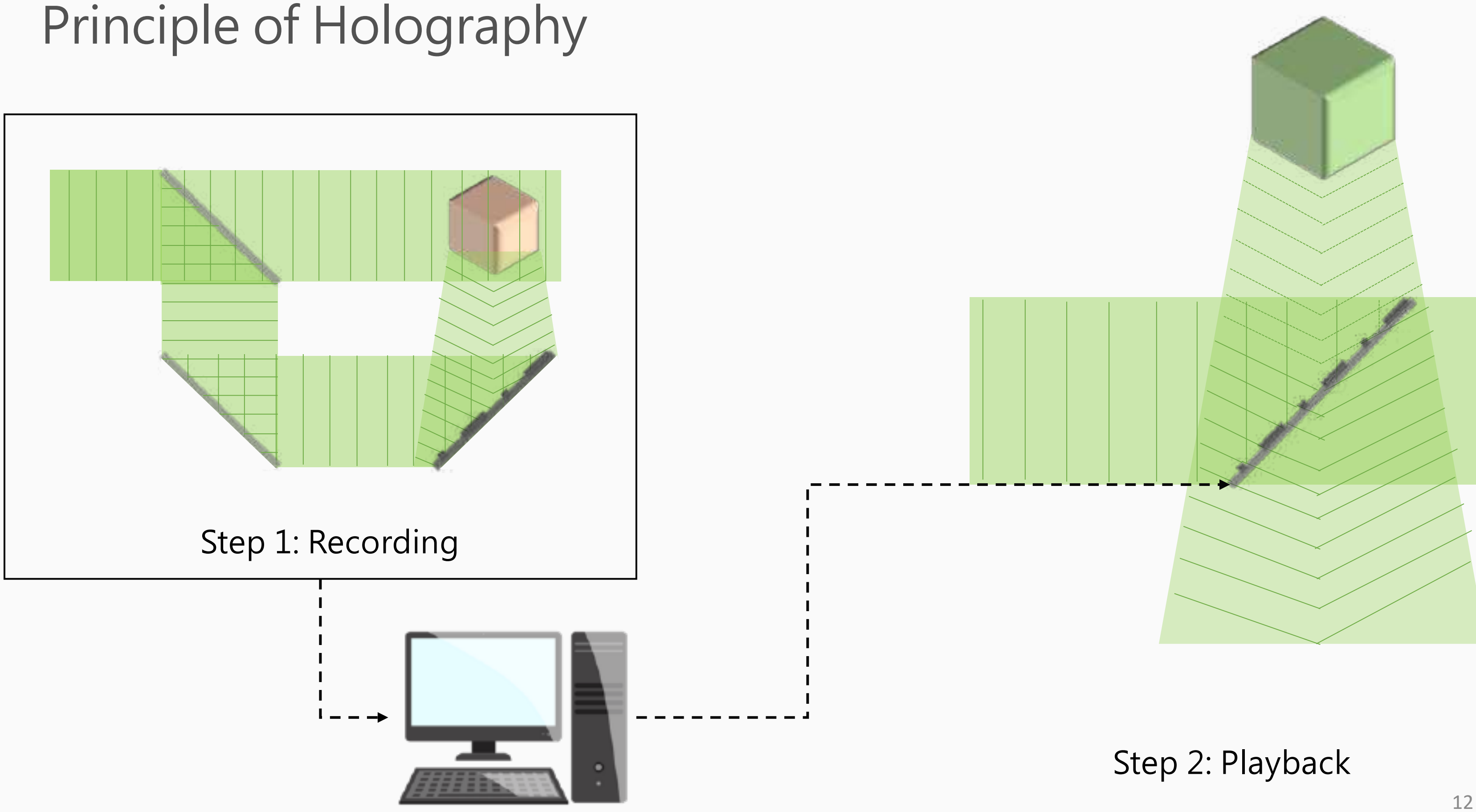
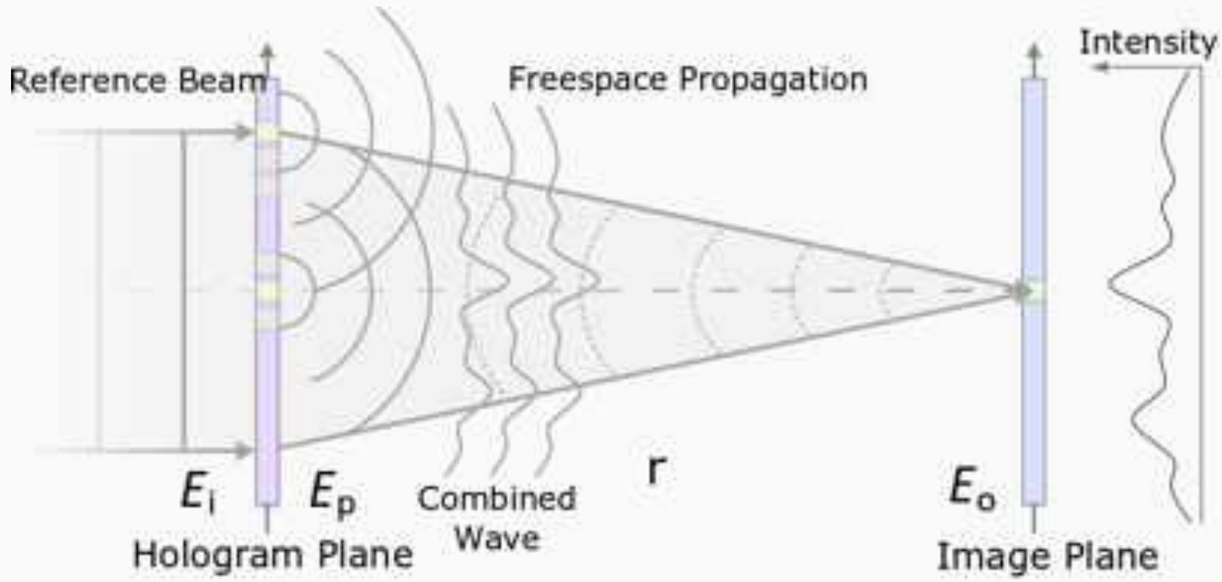
Principle of Holography



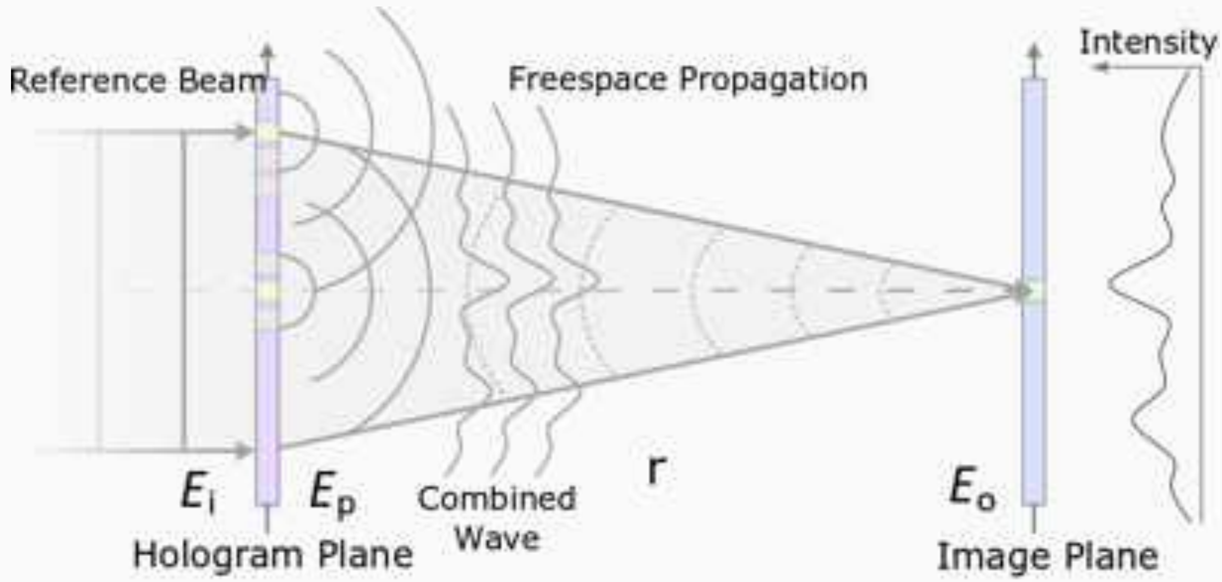
Holographic Image Formation



H

Incident light modulated by Hologram H

Holographic Image Formation

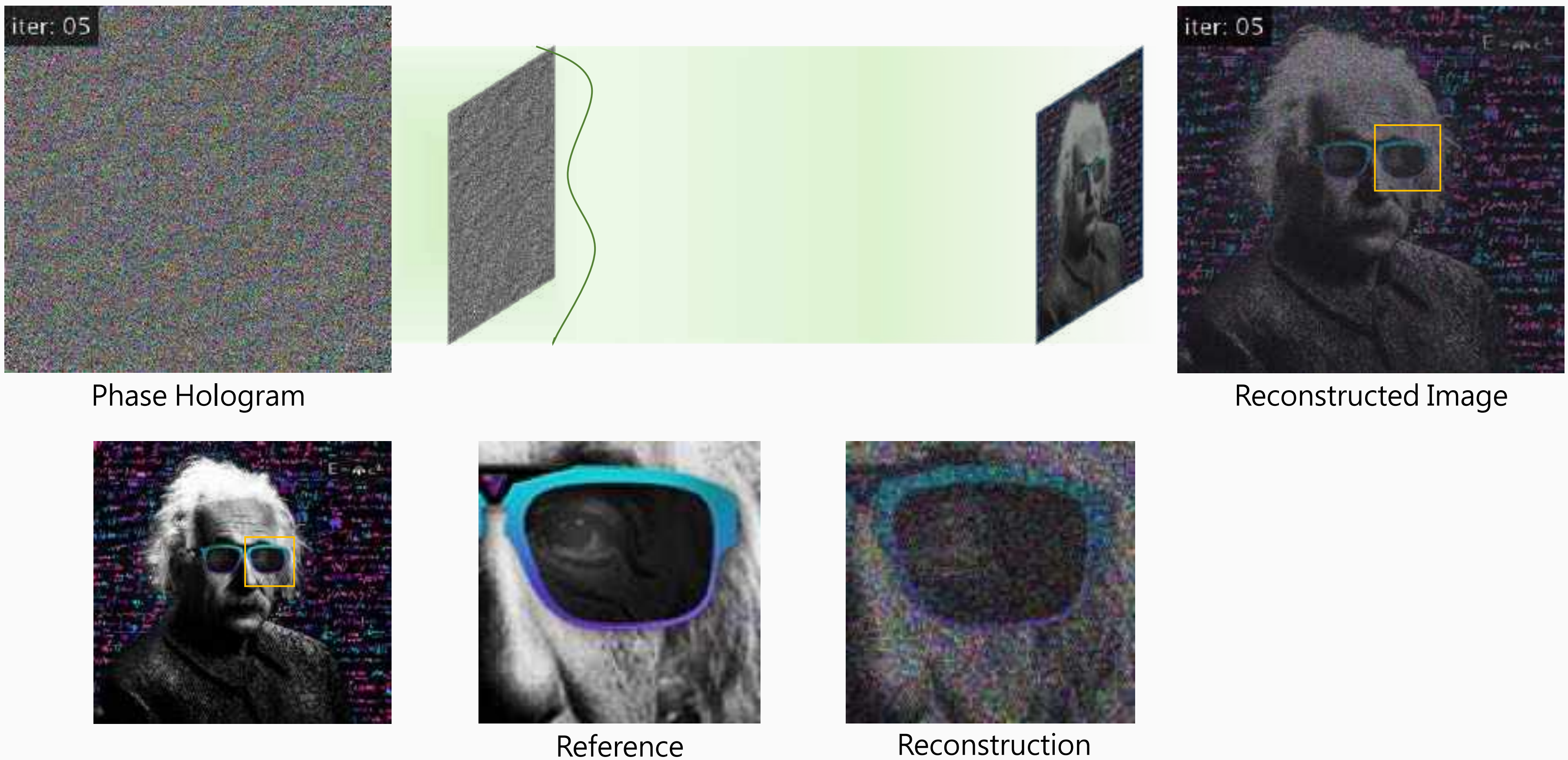


$$z = \mathcal{P}(H)$$

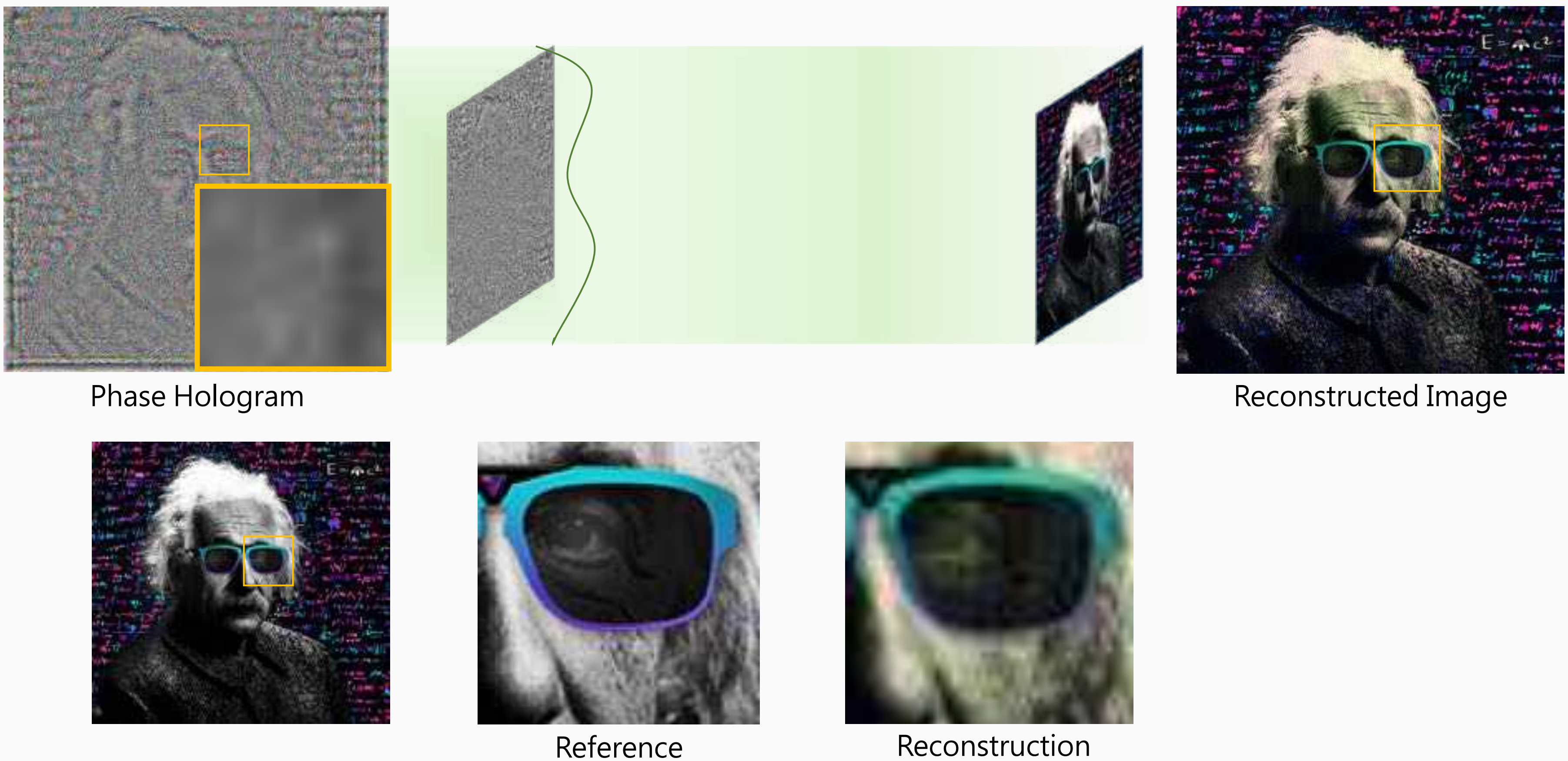
Propagates to result in the final field z

and final image $|z|^2$

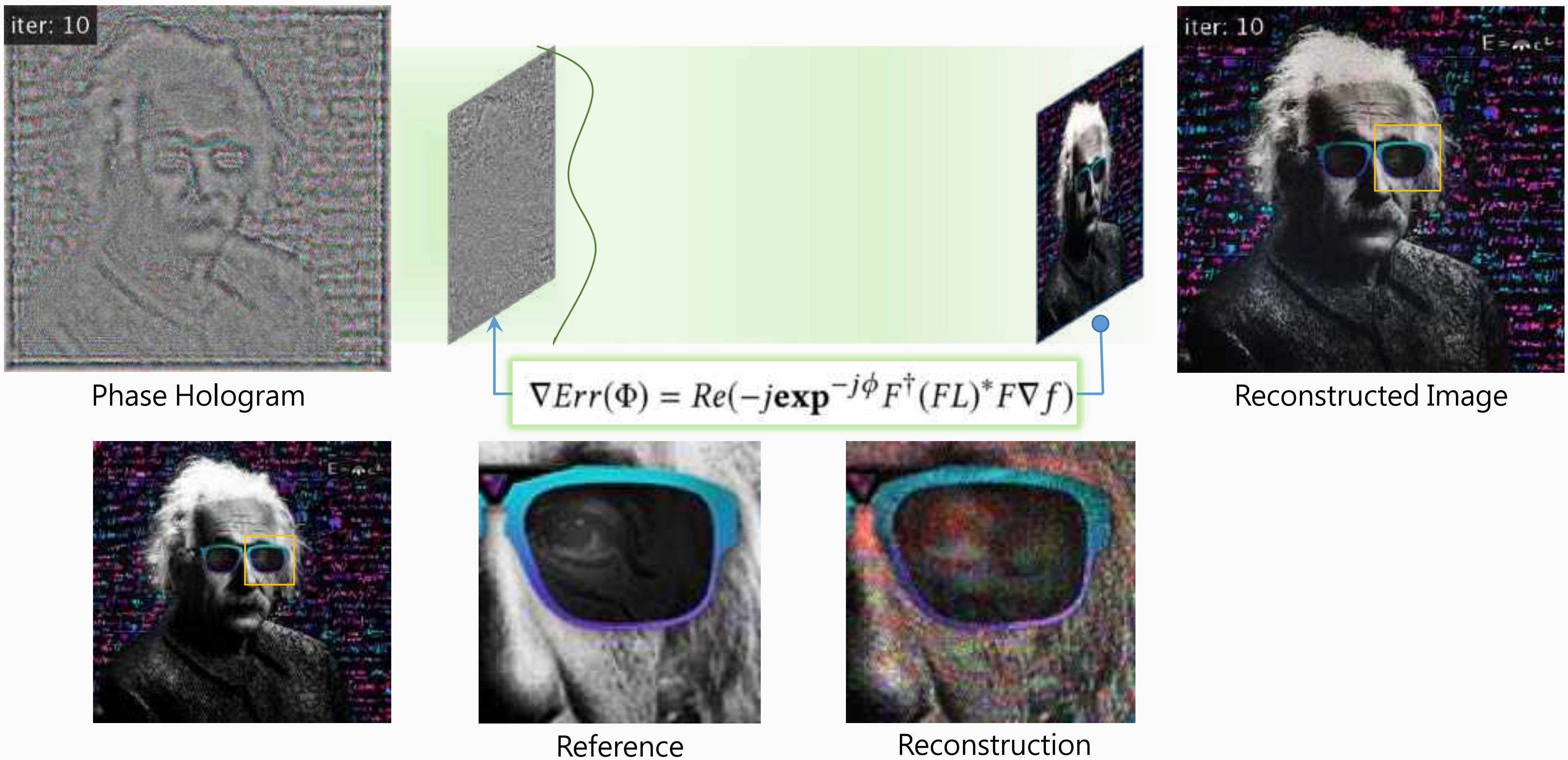
Heuristic Hologram Phase Retrieval



Double Phase Encoding Hologram



Wirtinger Holography



Wirtinger Holography

Wirtinger Holography Overview

Differentiable forward model → Compute complex Wirtinger gradients → Optimize for phase holograms

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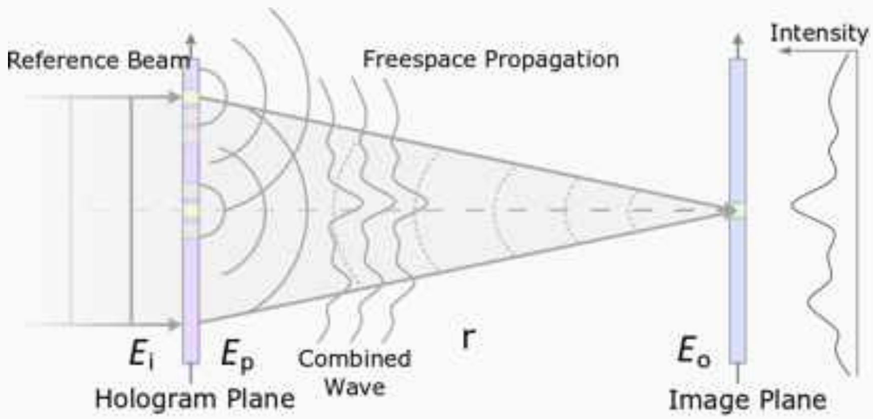
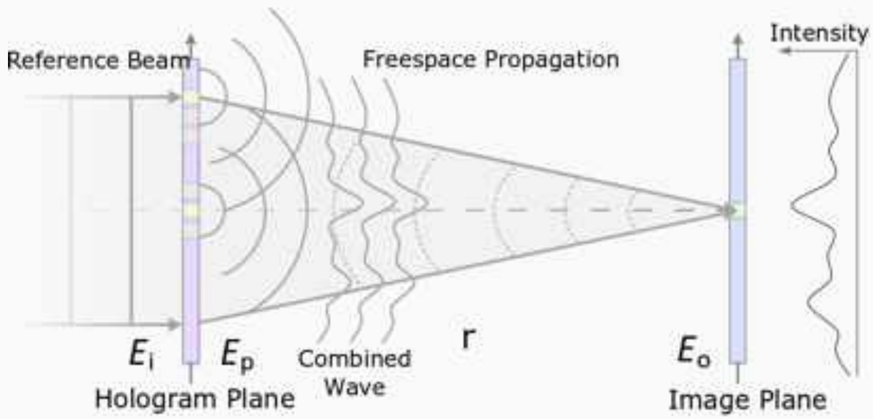


$$z = \mathcal{P}(H)$$

$$Err = f(|z|^2, I) = f(z)$$

Step 1: For a penalty function

Differentiable forward model → Compute complex Wirtinger gradients → Optimize for phase holograms

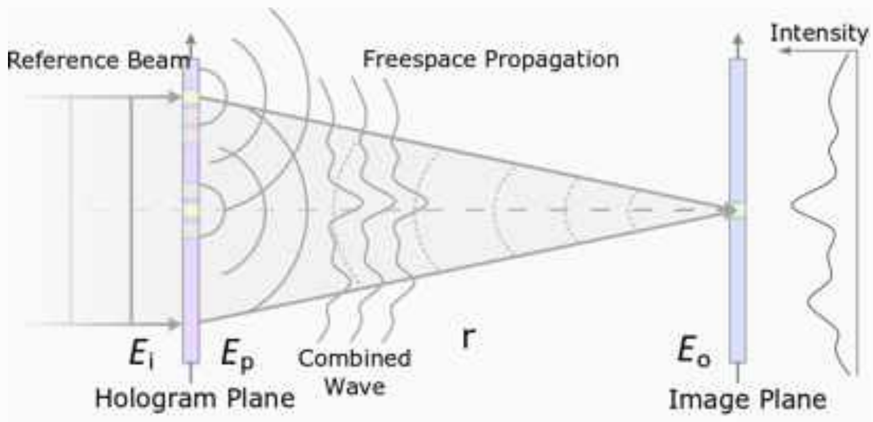


$$z = \mathcal{P}(H)$$

$$Err = f(|z|^2, I) = f(z)$$

Step 1: For a penalty function *f*, compute the error

Differentiable forward model → Compute complex Wirtinger gradients → Optimize for phase holograms

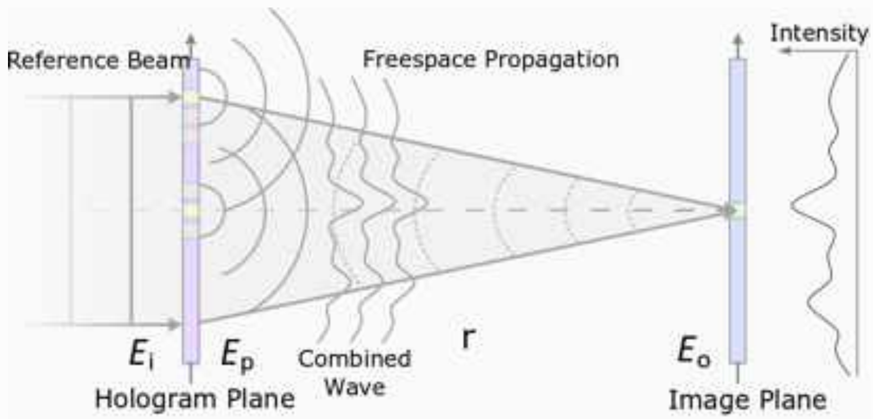


$$z = \mathcal{P}(H)$$

$$Err = f(|z|^2, I) = f(z)$$

Step 1: For a penalty function *f*, compute the error between the holographic reconstruction and

Differentiable forward model → Compute complex Wirtinger gradients → Optimize for phase holograms



$$z = \mathcal{P}(H)$$

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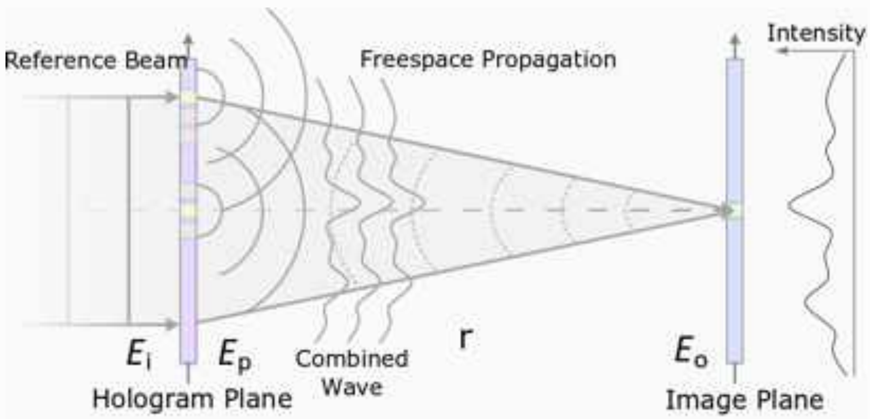
Step 1: For a penalty function *f*, compute the error between the holographic reconstruction and the target image

Differentiable forward model → Compute complex Wirtinger gradients → Optimize for phase holograms



$$z = \mathcal{P}(H)$$

$$H(\Phi) = c\mathbf{exp}^{j\Phi}$$

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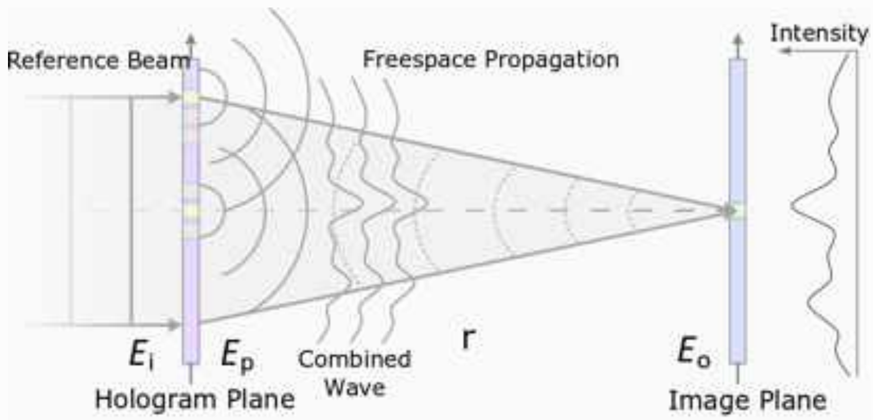
Differentiable forward model → Compute complex Wirtinger gradients → Optimize for phase holograms



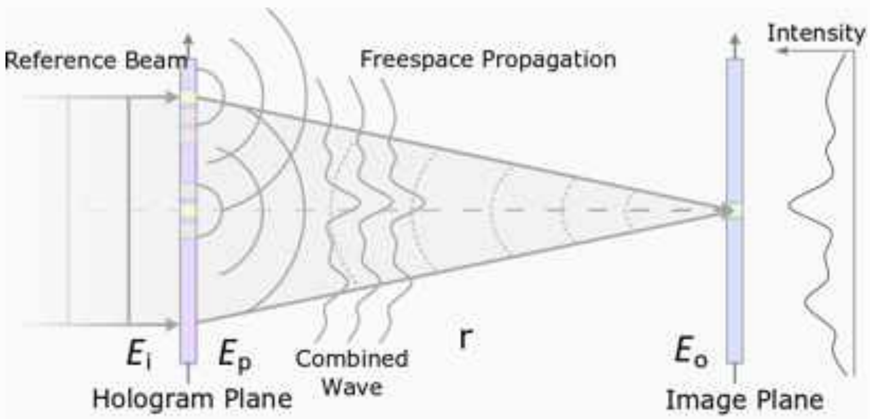
$$z = \mathcal{P}(H)$$

$$H(\Phi) = c\mathbf{exp}^{j\Phi}$$

$$Err = f(\underline{|\mathcal{P}(H(\Phi))|}^2, I)$$

Step 1: For a penalty function *f*, compute the error between the holographic reconstruction and the target image

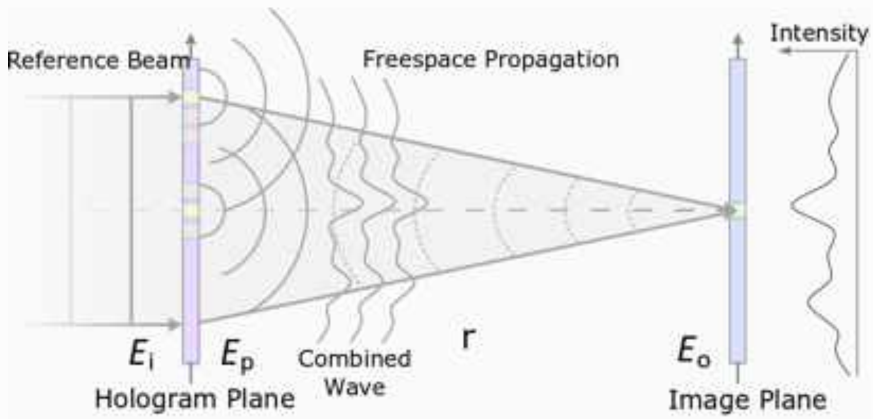
Differentiable forward model → Compute complex Wirtinger gradients → Optimize for phase holograms



$$\Phi_{opt} = \underset{\Phi}{\text{minimize}} \quad \underbrace{f(|\mathcal{P}(H(\Phi))|^2, I)}_{Err(\Phi)} + \gamma ||\nabla\Phi||^2$$

Step 2: Construct the cost function

Differentiable forward model → Compute complex Wirtinger gradients → Optimize for phase holograms



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Step 2: Construct the cost function to minimize the error e

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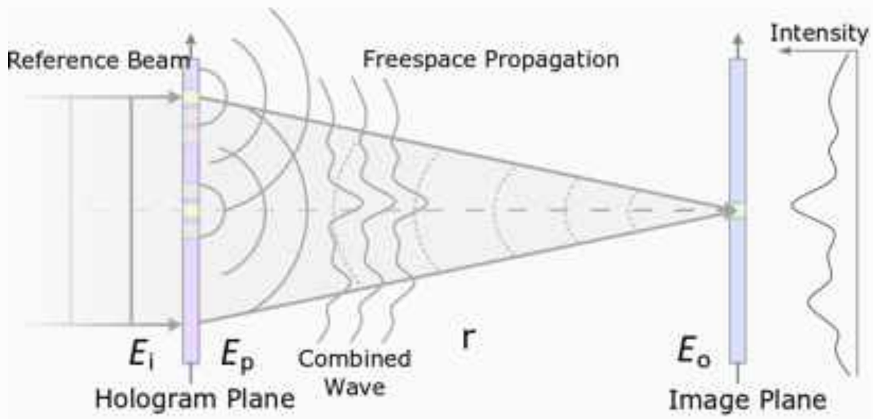

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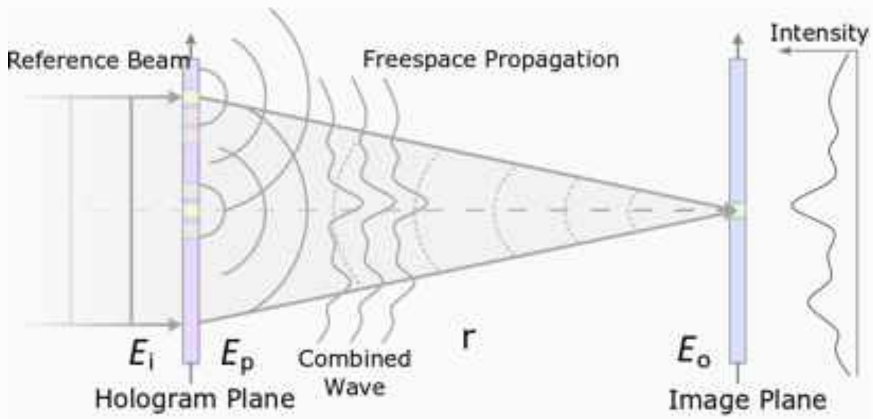
Step 2: Construct the cost function to minimize the error with optional regularizer

Differentiable forward model → Compute complex Wirtinger gradients → Optimize for phase holograms



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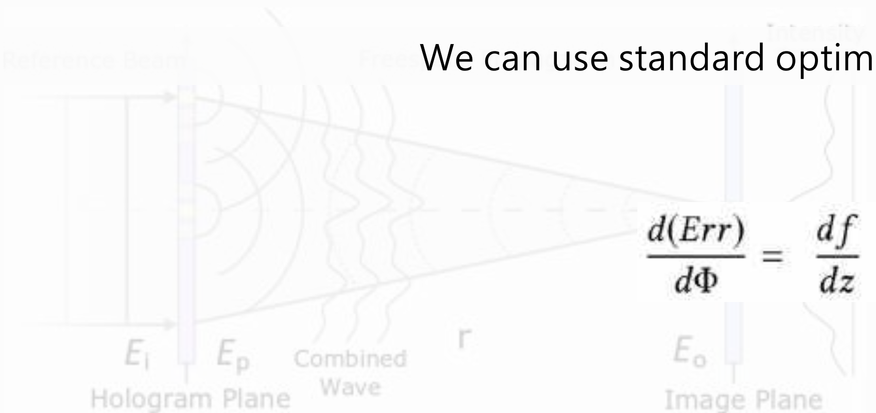
Step 2: Construct the cost function to minimize the error with optional regularizer to obtain the optimal phase

Differentiable forward model → Compute complex Wirtinger gradients → Optimize for phase holograms

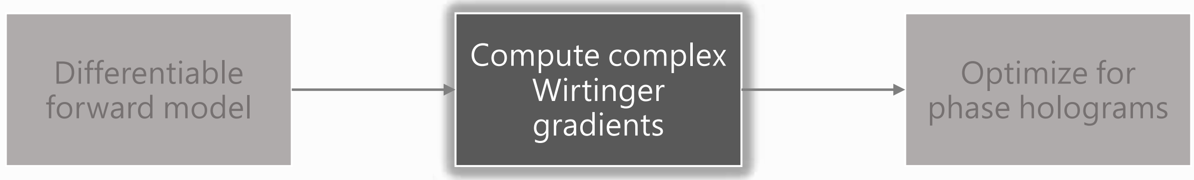


We can use standard optimizers if there is a gradient

$$\Phi_{opt} = \underset{\Phi}{\text{minimize}} \quad \underbrace{f(|\mathcal{P}(H(\Phi))|^2, I)}_{Err(\Phi)} + \gamma ||\nabla\Phi||^2$$

$$\frac{d(Err)}{d\Phi} = \frac{df}{dz} \quad \frac{dz}{dH} \quad \frac{dH}{d\Phi}$$

Step 2: Construct the cost function to minimize the error with optional regularizer to obtain the optimal phase



Holomorphic function: Complex function that is complex differentiable

Derivative of holomorphic real-valued function is always <u>**ZERO**</u>

$$\Phi_{opt} = \underset{\Phi}{\text{minimize}} \quad \underbrace{f(|\mathcal{P}(H(\Phi))|^2, I)}_{Err(\Phi)} + \gamma||\nabla\Phi||^2$$

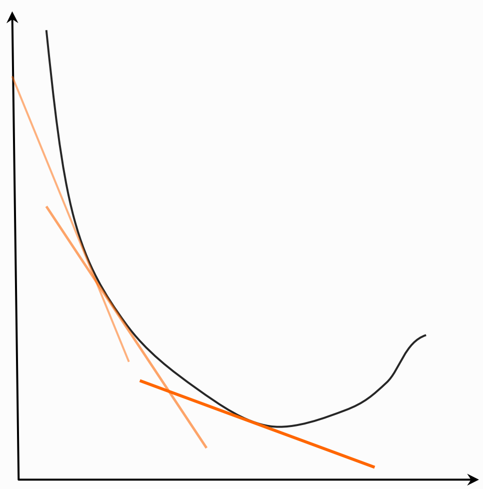
$$\frac{d(Err)}{d\Phi} = \frac{df}{dz}\,\frac{dz}{dH}\,\frac{dH}{d\Phi}$$

Real-valued function

Complex-valued argument

Derivatives of any order are **NOT DEFINED** for our objective function

Differentiable forward model → **Compute complex Wirtinger gradients** → Optimize for phase holograms



Two important properties of gradient:

1) Direction of maximal rate of change

2) Is zero at stationary points

$$d(Err) = df(z) = Re\langle \nabla f, dz \rangle$$

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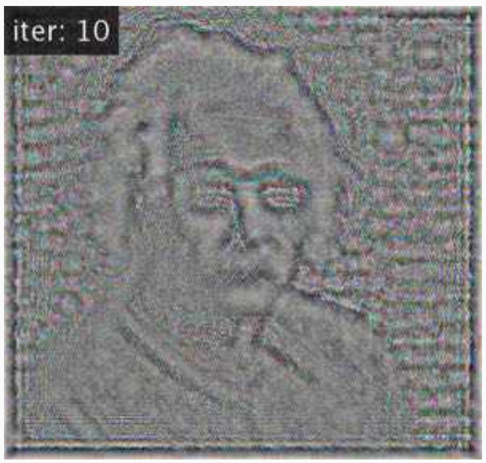
PAPER AND SUPPLEMENT

Step 3: Define approximate gradient and compute Wirtinger derivatives for each propagation model

Differentiable forward model → Compute complex Wirtinger gradients → **Optimize for phase holograms**



Standard off-the-shelf optimization methods

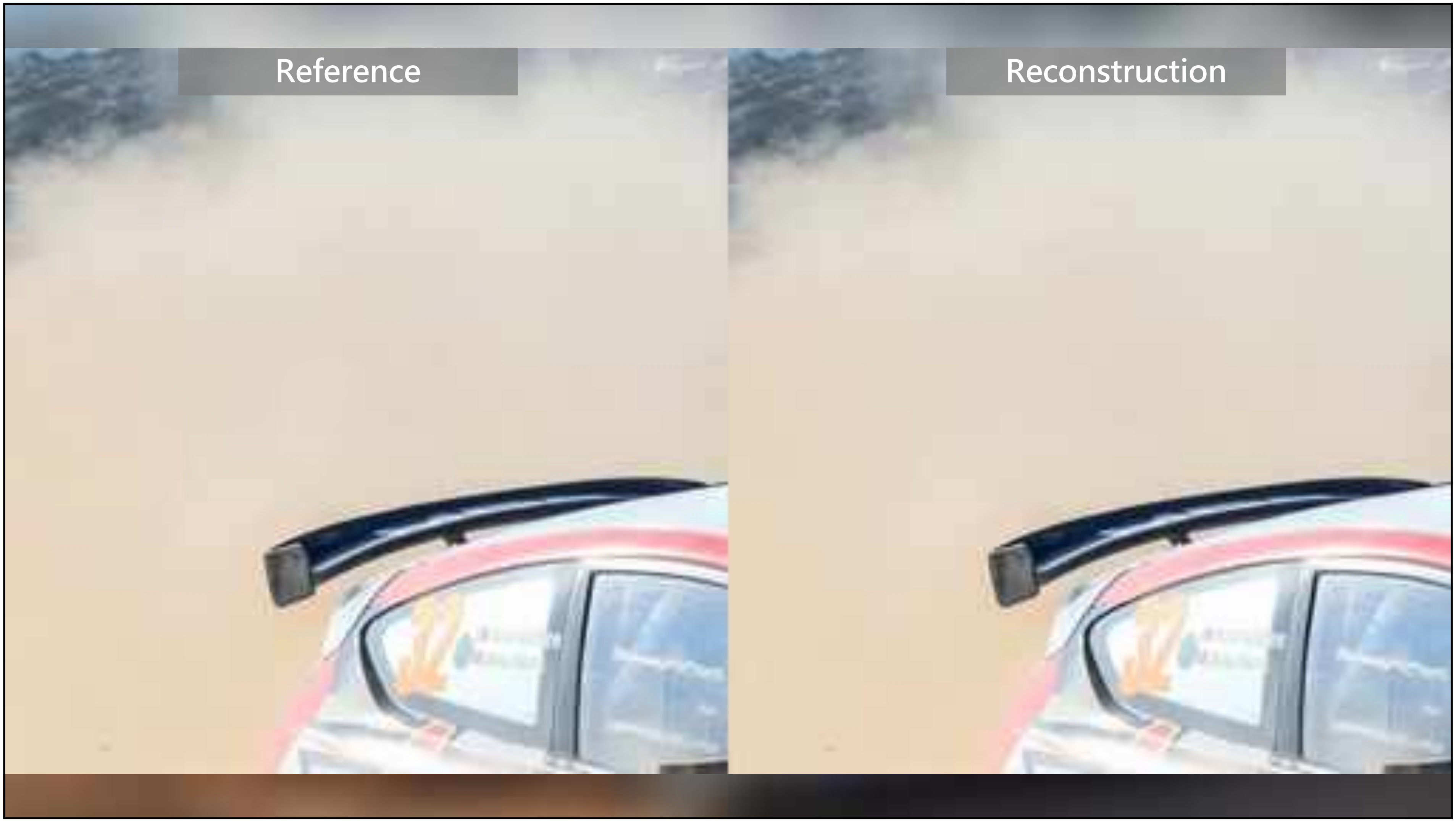
1) Quasi-Newton

2) Stochastic gradient descent

Step 4: Optimize for holograms using off-the-shelf methods

Simulation Results


Reference
Reconstruction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Reconstruction

Simulation Results

Target | Modified GS (Peng et al. 2017) | Double phase (Maimone et al. 2017) | Our Method

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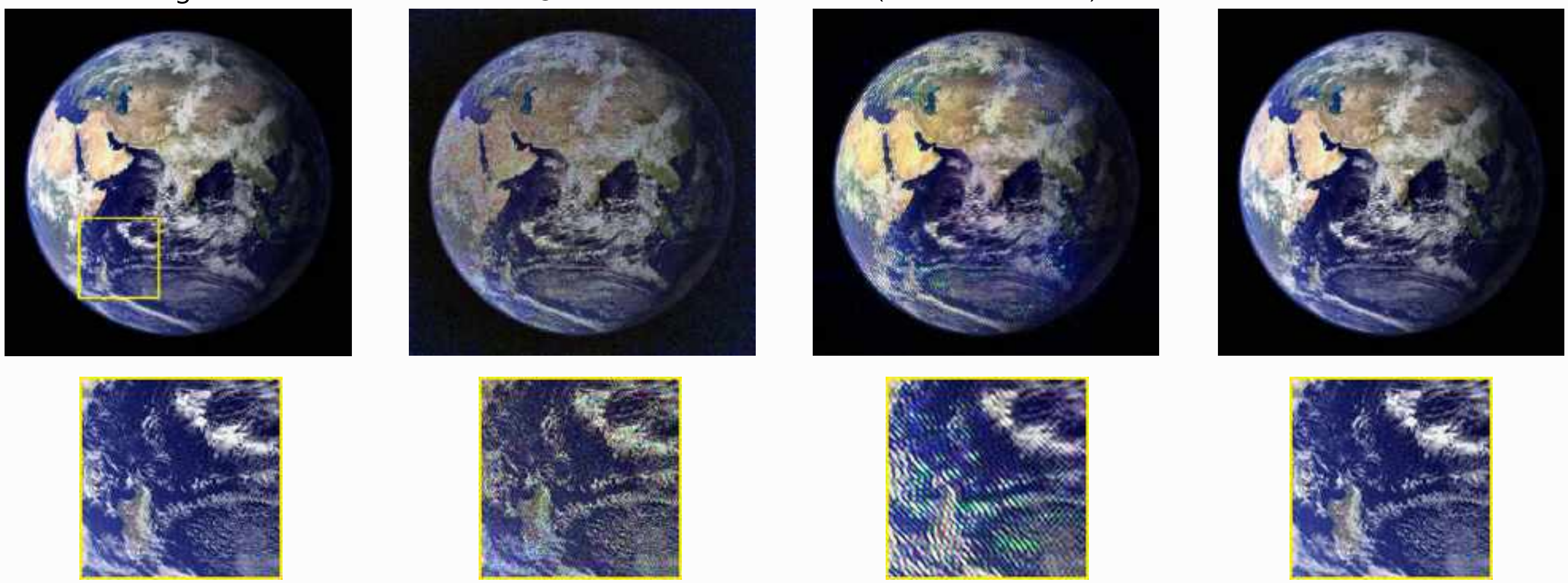
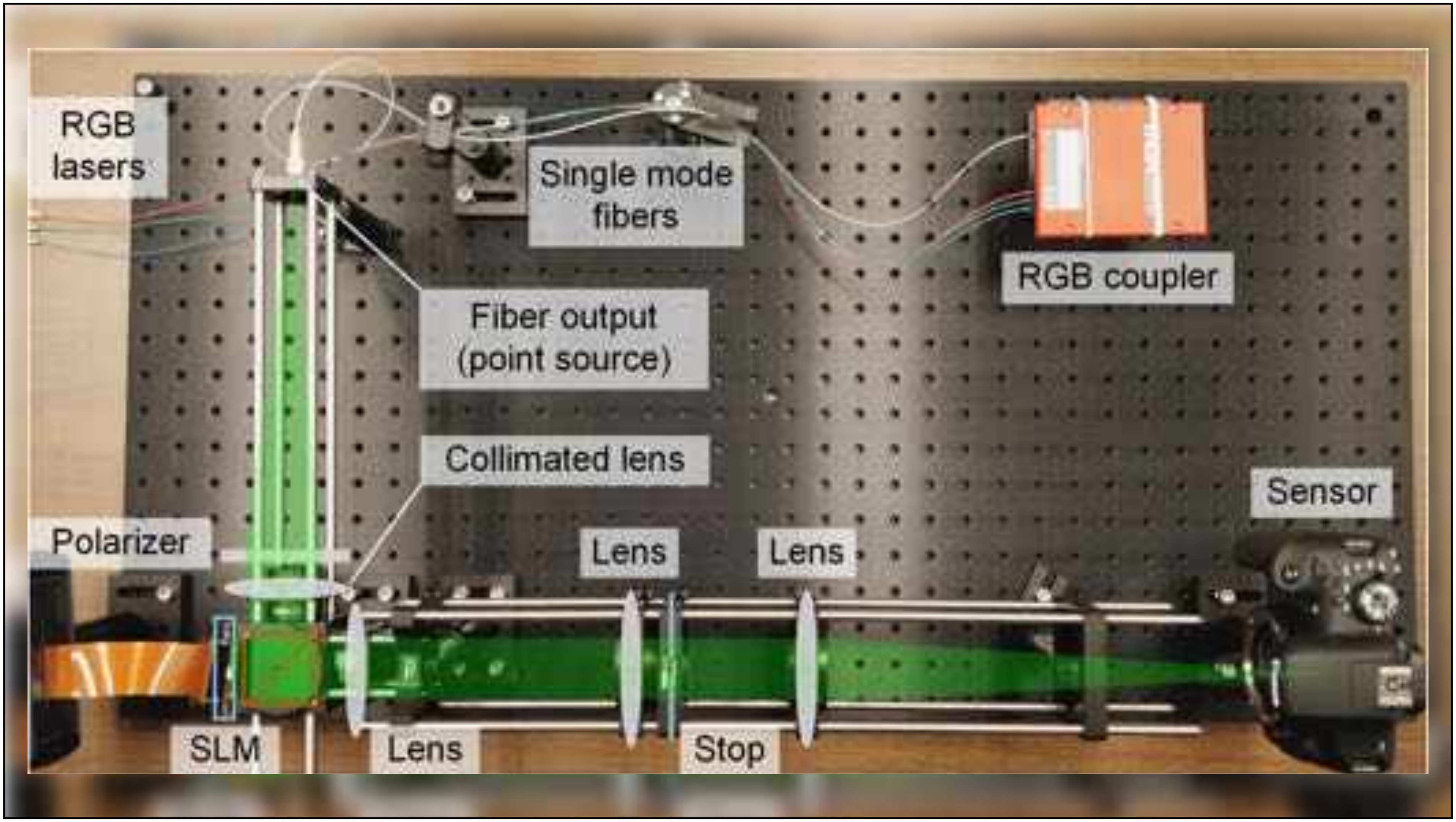
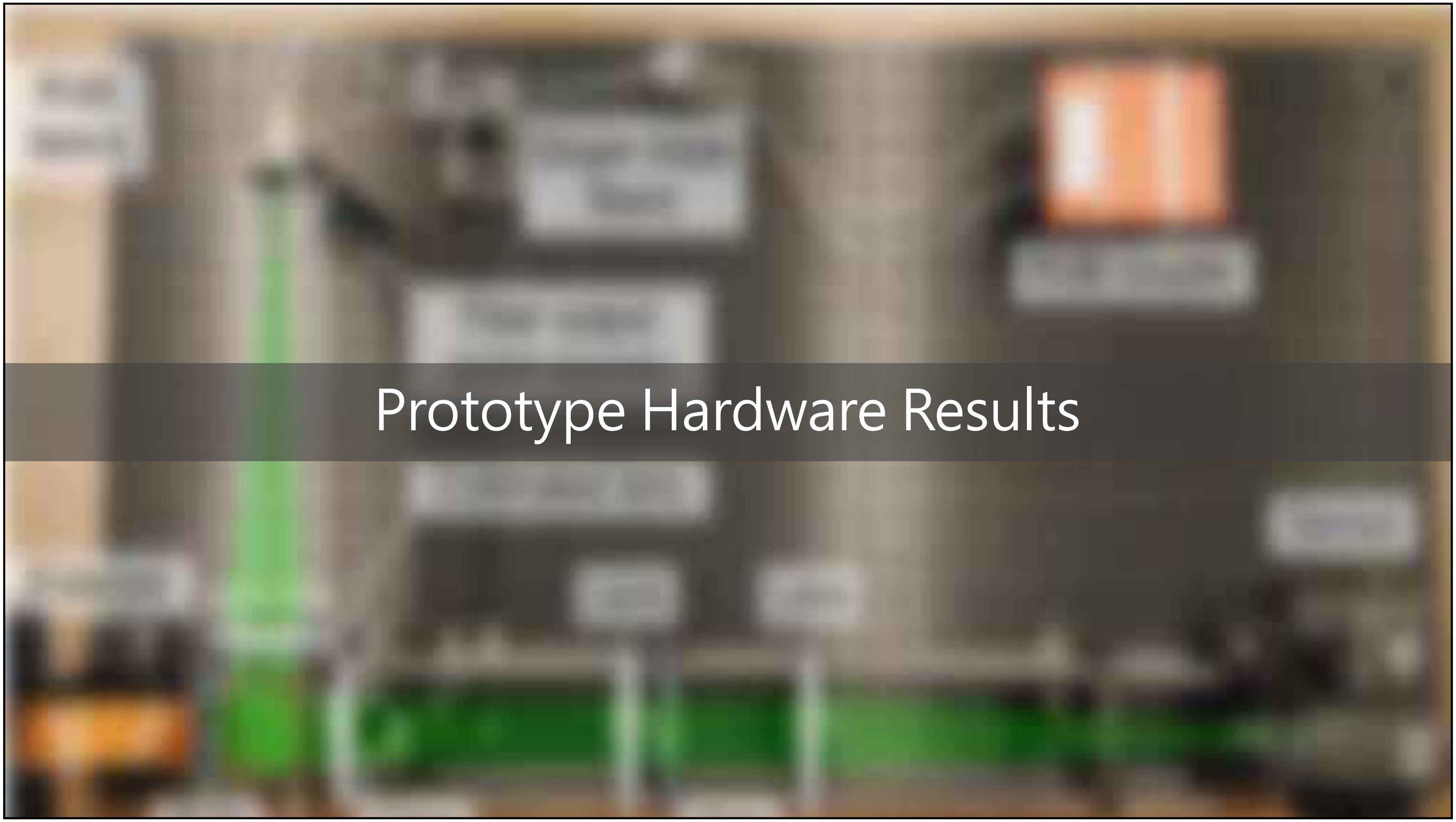




RGB lasers
Single mode fibers
RGB coupler
Fiber output (point source)
Collimated lens
Sensor
Polarizer
Lens
Lens
SLM
Lens
Stop



Prototype Hardware Results

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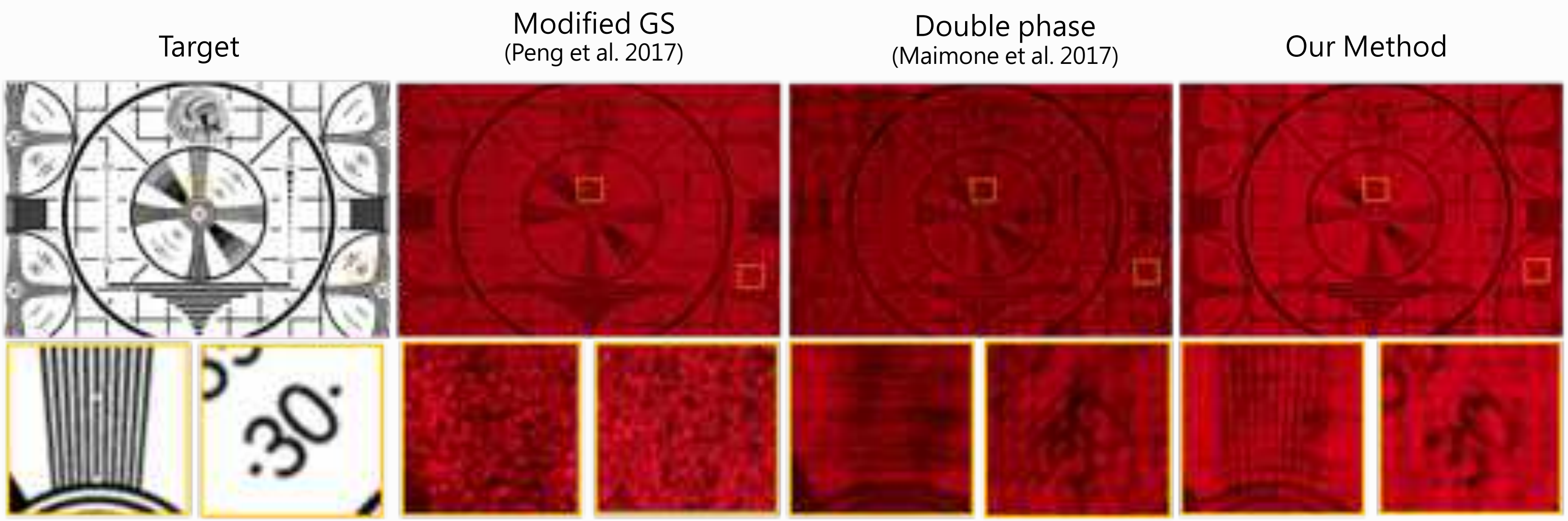

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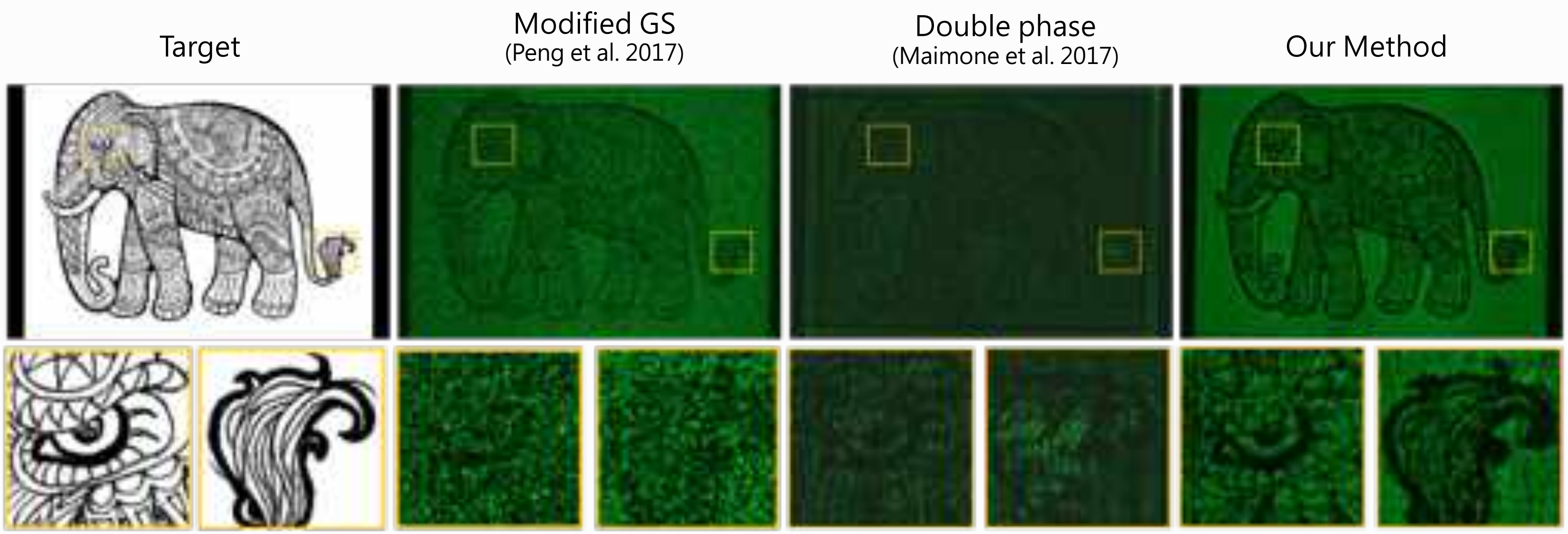

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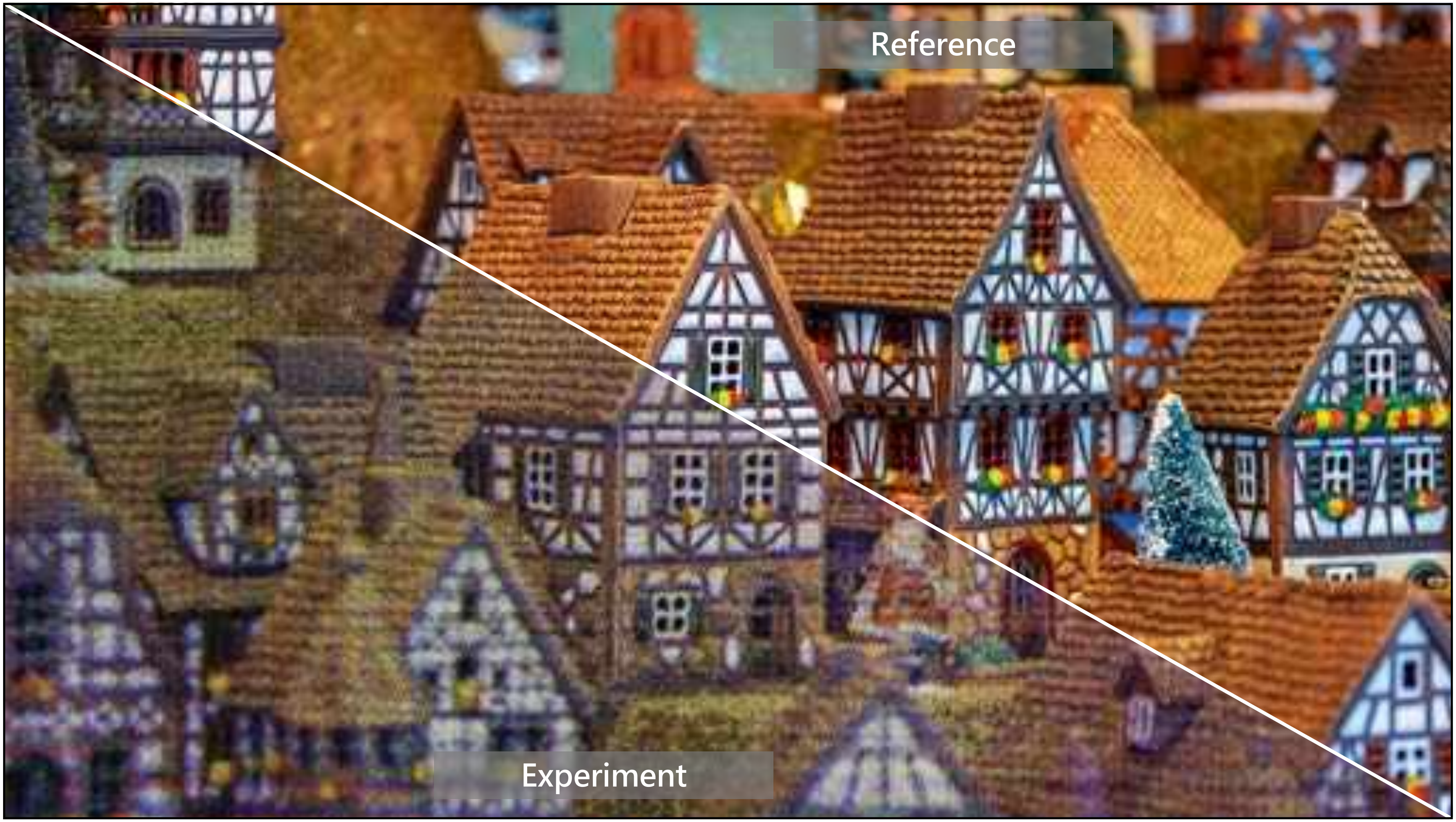
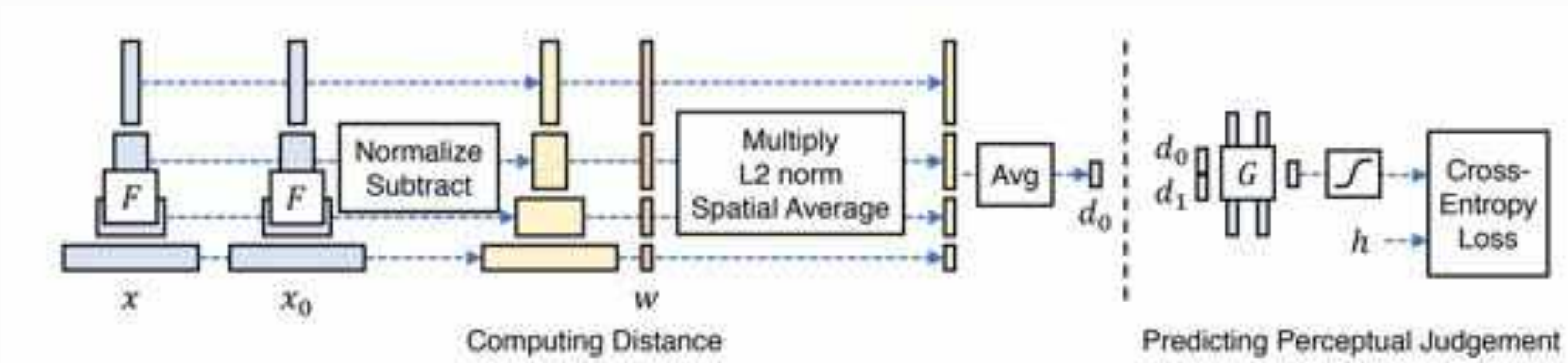

Reference
Experiment


Reference
Experiment

Perceptually Optimized Holography

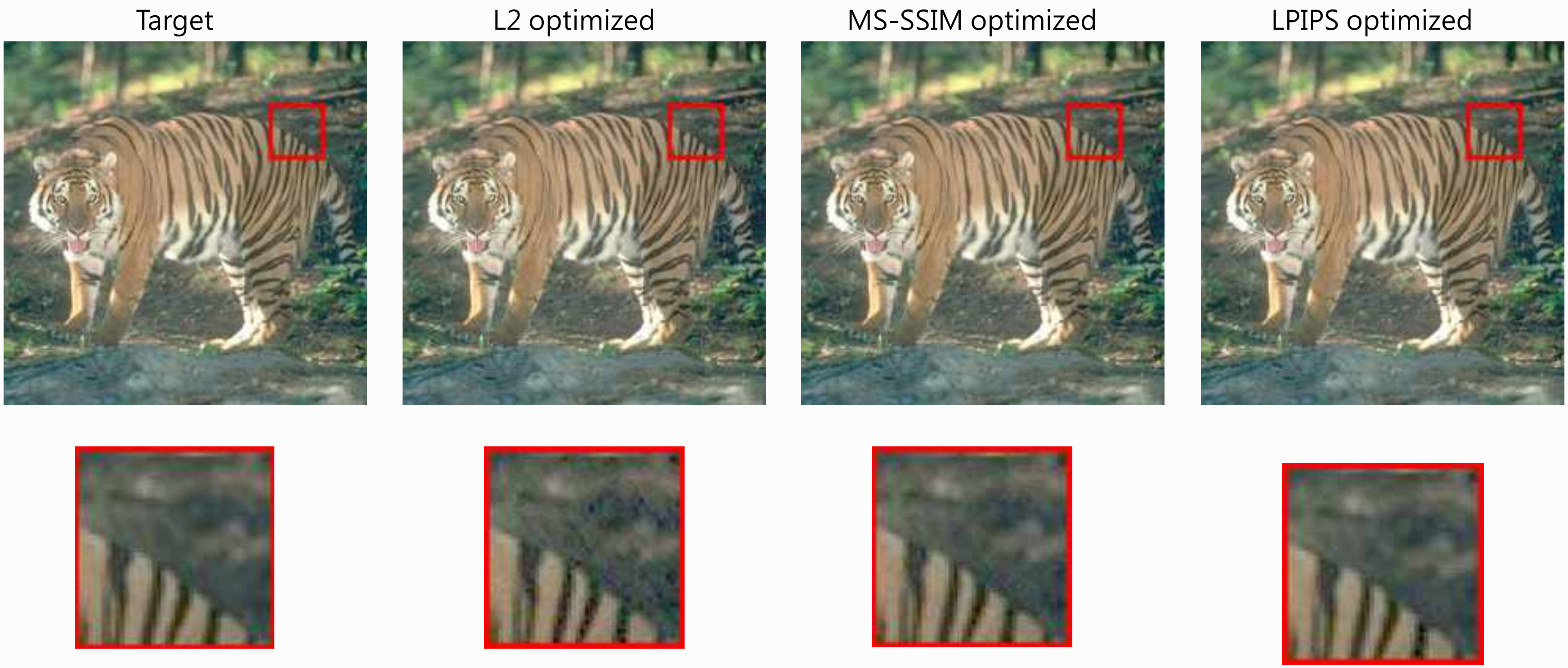
Optimize for deep learning based perceptual losses



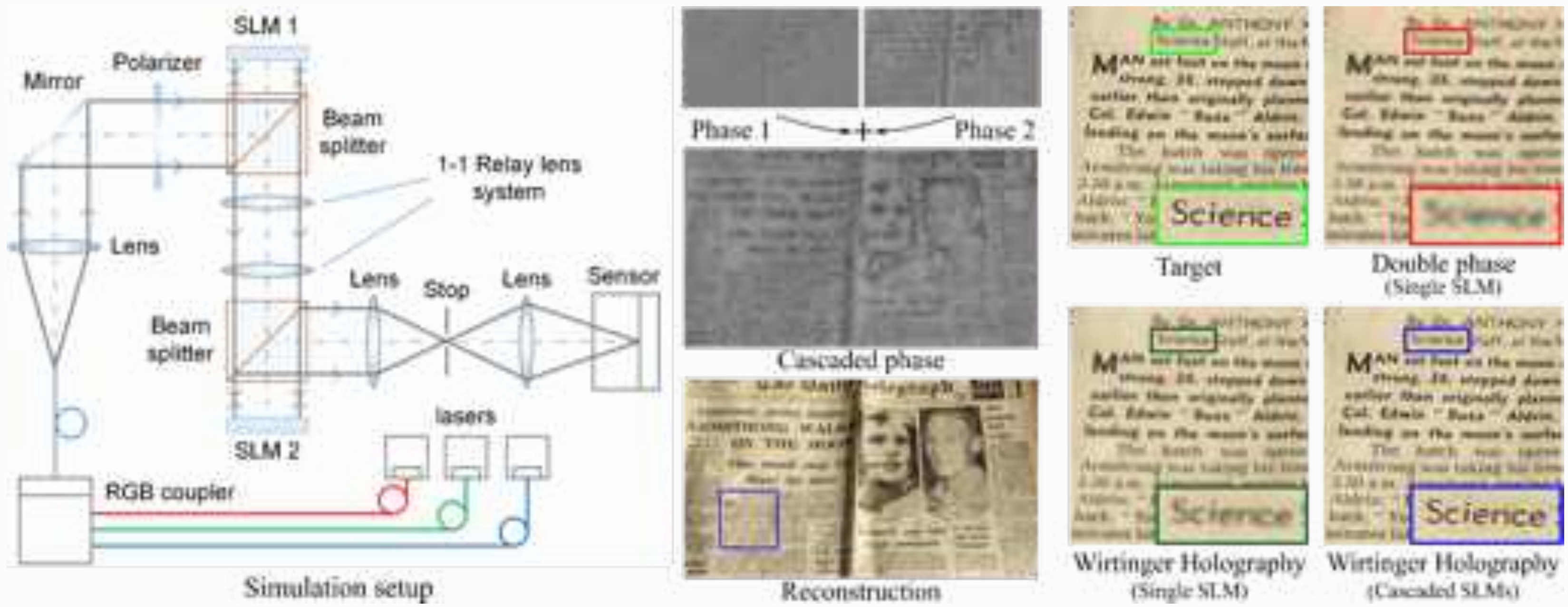
Learned Perceptual Image Patch Similarity (LPIPS)

(Zhang et al. 2018)

Perceptually Optimized Holography



Cascaded Superresolution Holography



Simulation setup

Cascaded phase

Reconstruction

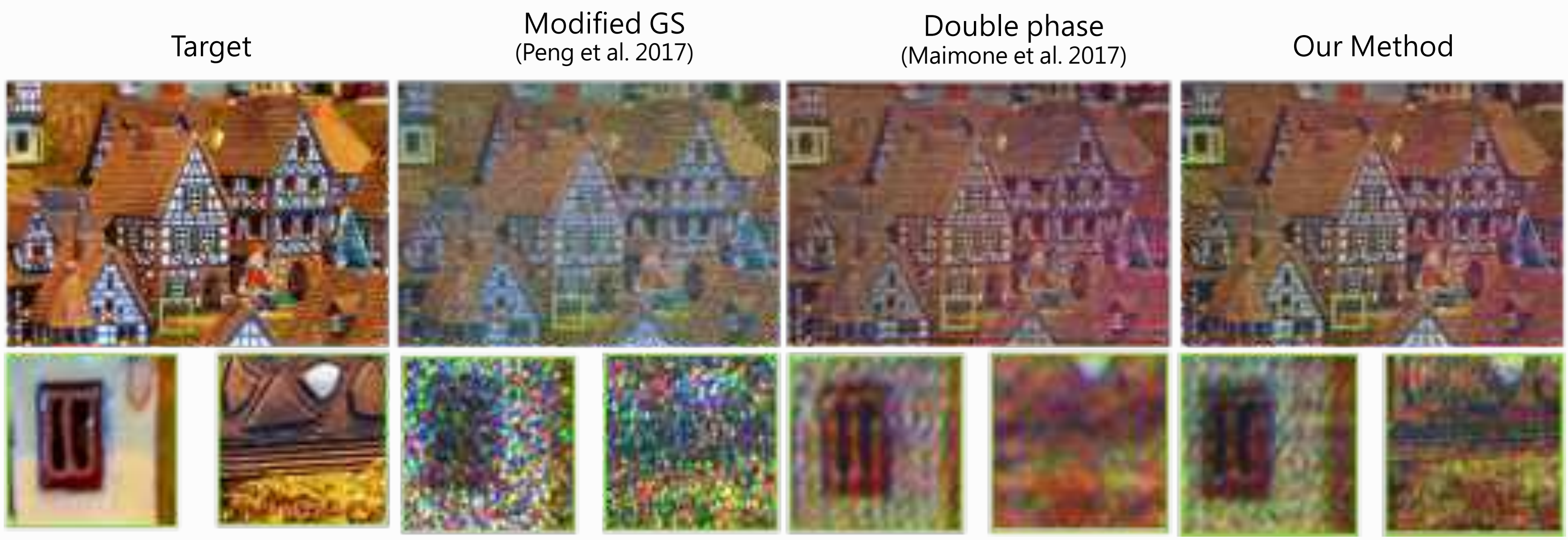
Target

Double phase (Single SLM)

Wirtinger Holography (Single SLM)

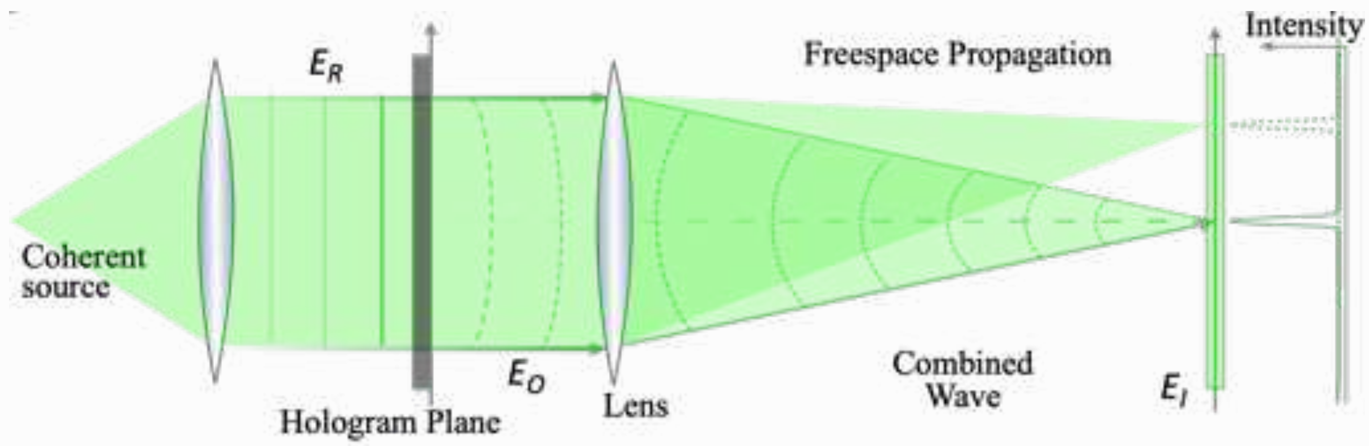
Wirtinger Holography (Cascaded SLMs)

Prototype Hardware Results

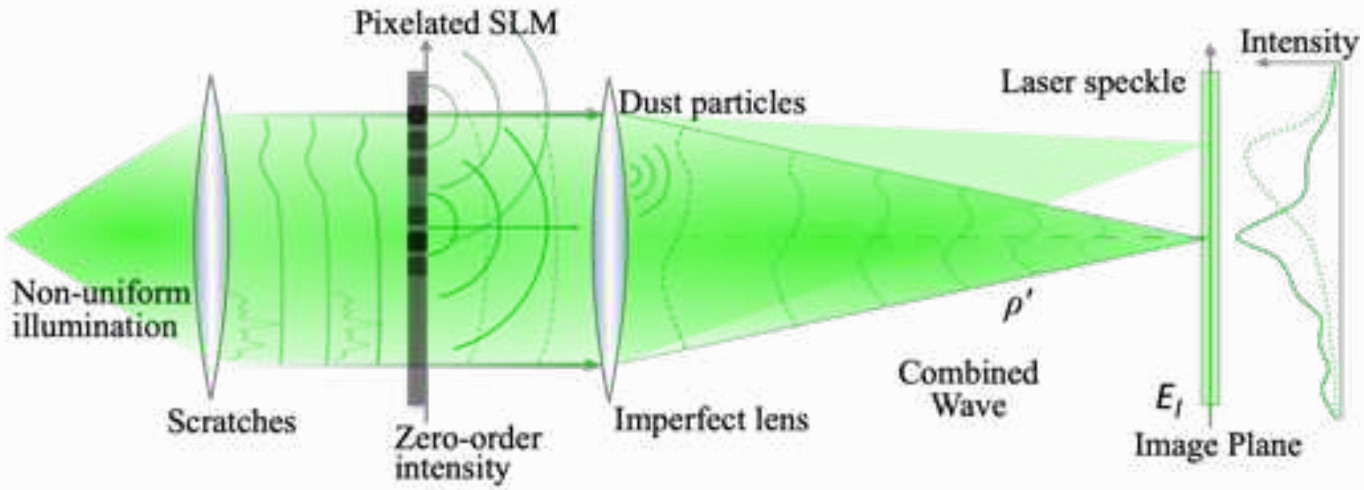


Real World Deviations

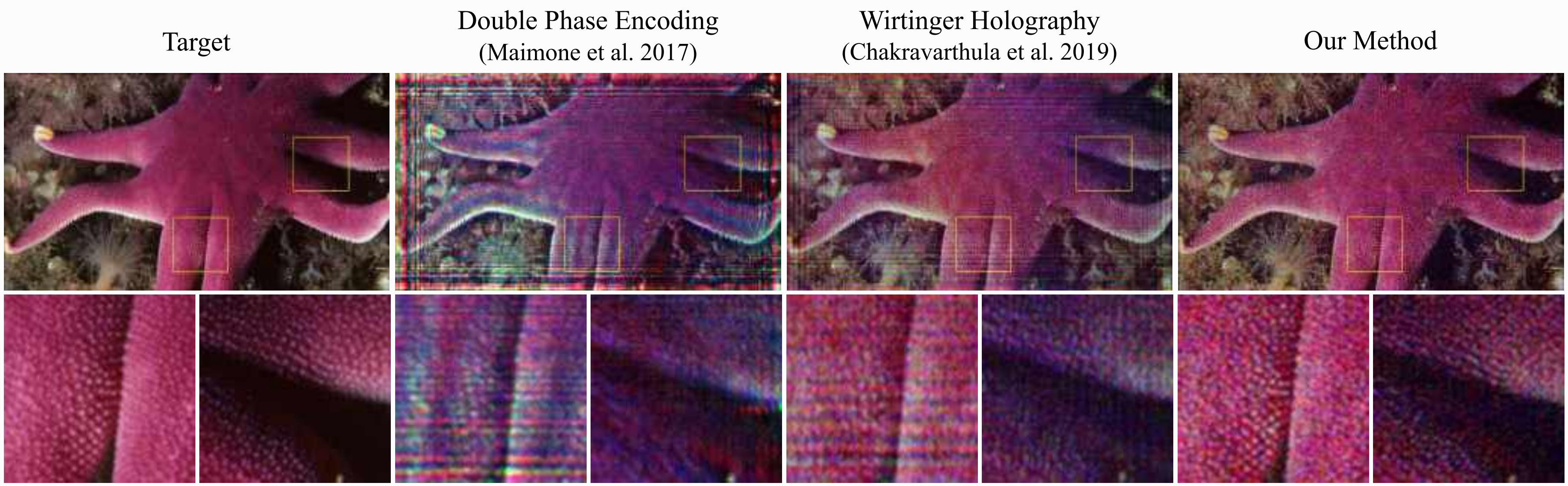
Ideal Wave Propagation



Real World Wave Propagation

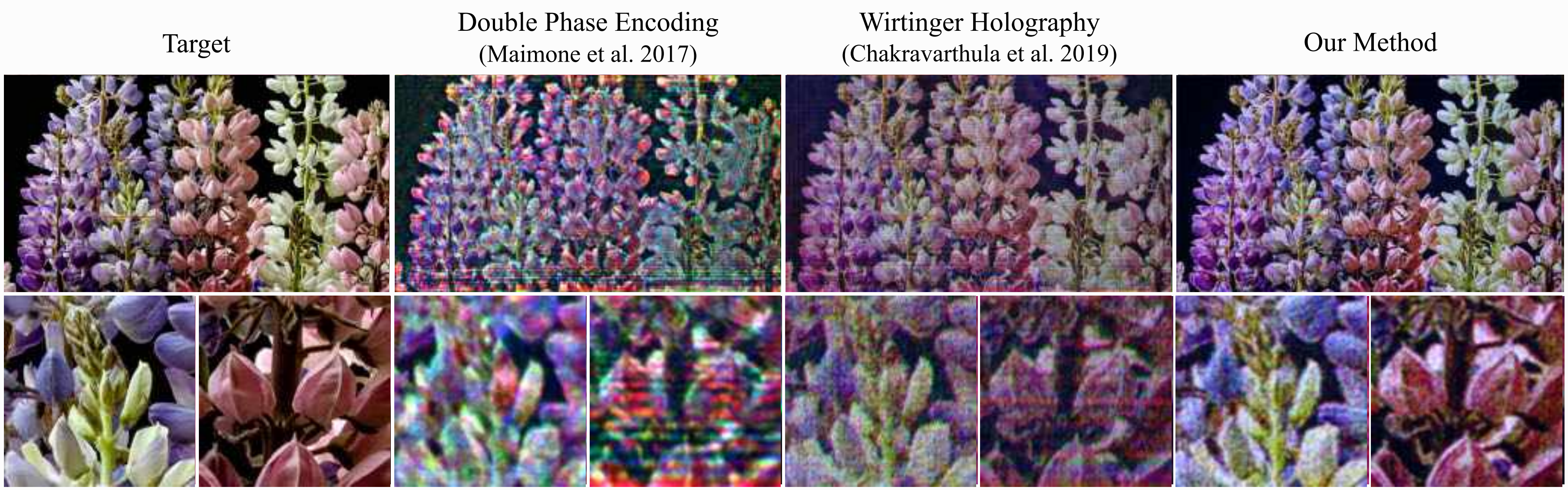


Compensating real world deviations via Hardware-in-the-loop phase retrieval



Upcoming at SIGGRAPH Asia 2020

Compensating real world deviations via Hardware-in-the-loop phase retrieval

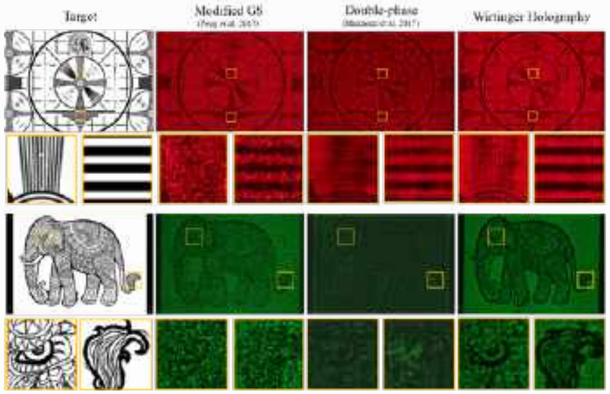


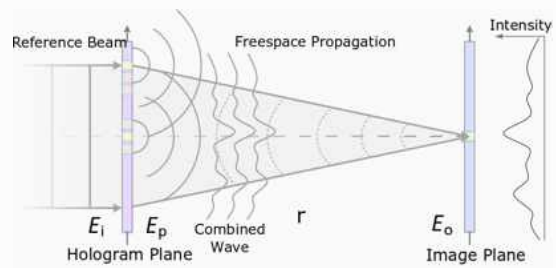
Upcoming at SIGGRAPH Asia 2020

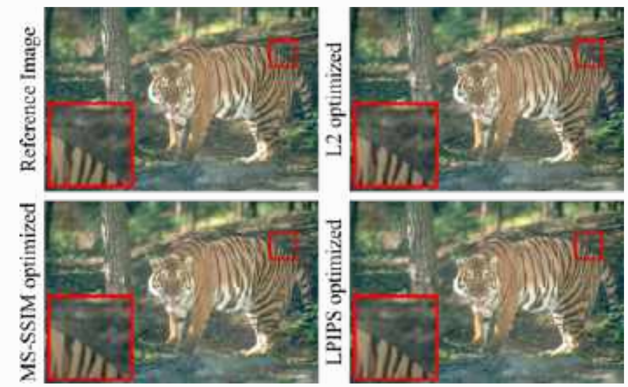
Differentiable forward model → Compute complex Wirtinger gradients → Optimize for phase holograms

Praneeth Chakravarthula

www.cs.unc.edu/~cpk







Wirtinger Holography