SIGGRAPH ASIA 2025 香港 HONG KONG

Designing and Fabricating Color BRDFs with Differentiable Wave Optics

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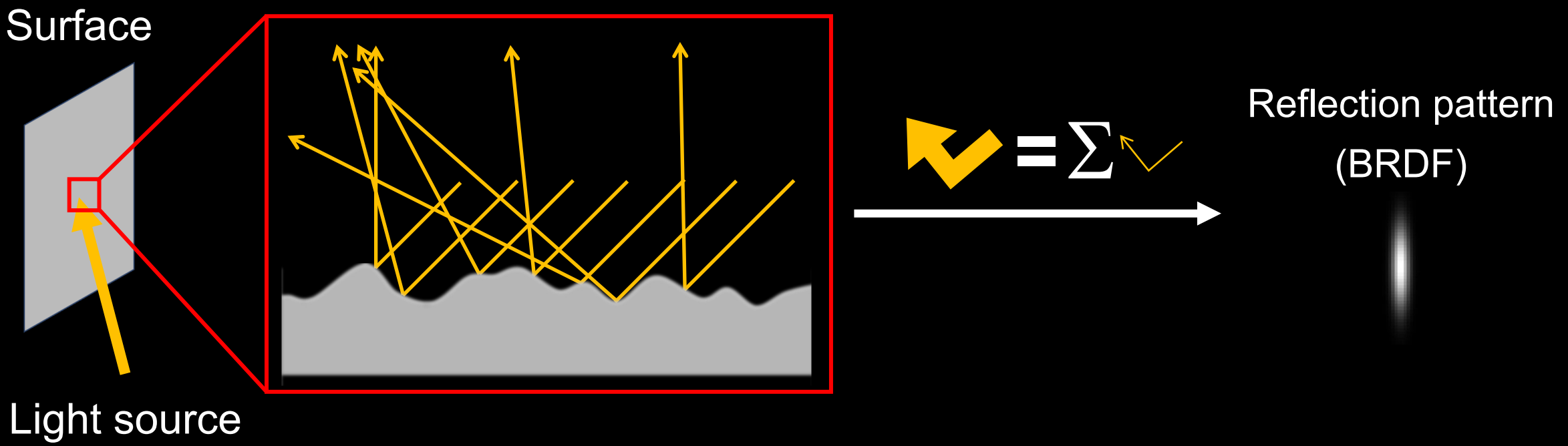
Introduction

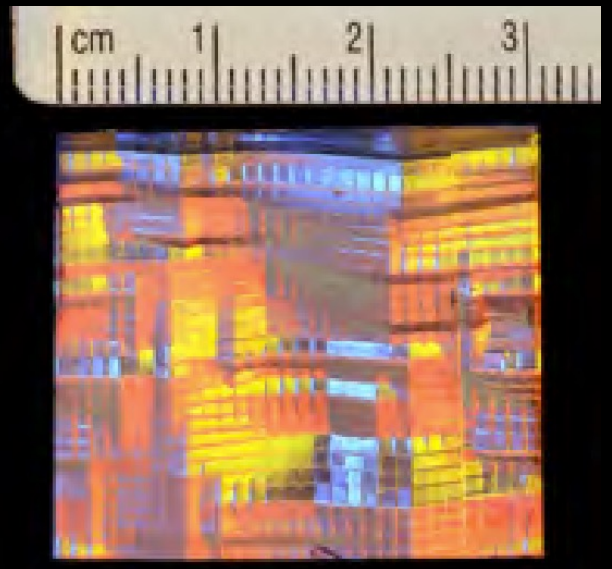
Geometric Surface BRDF Rendering

- Microfacet theory

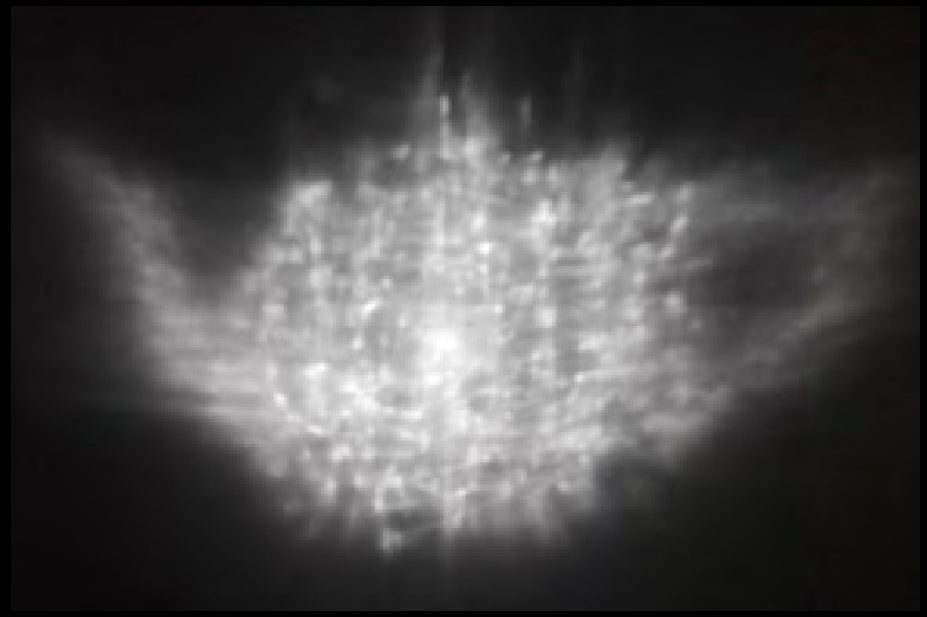


Design Custom BRDF

- Manufacture surfaces that exhibit a desired appearance



Surface Geometry

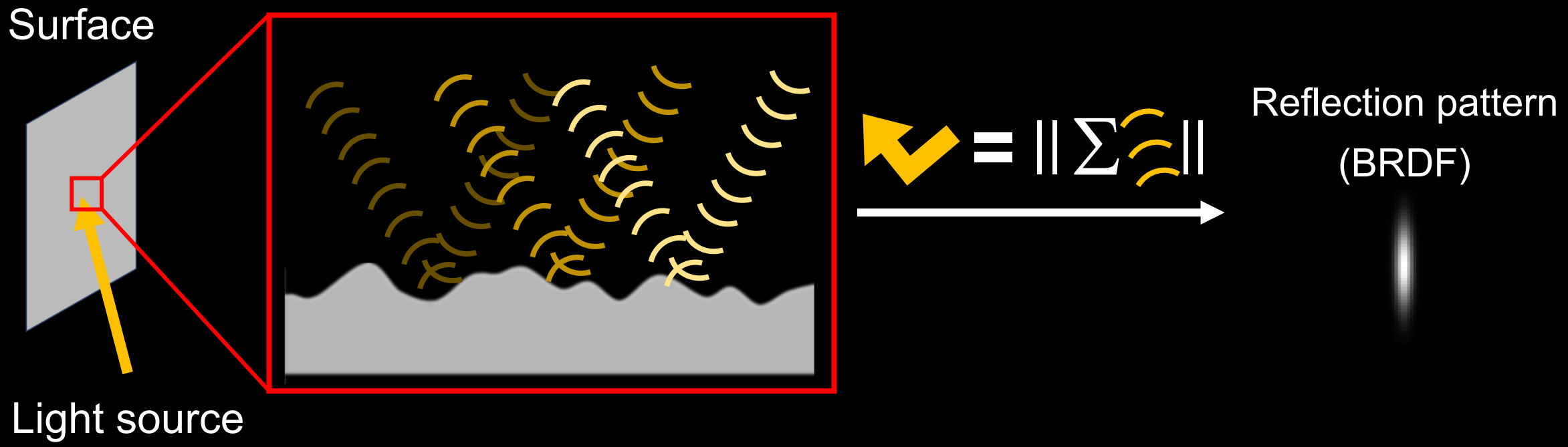


Reflectance

[Weyrich et al. 2009]

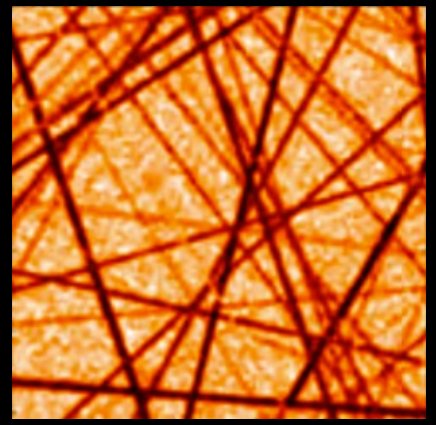
Wave Optics Surface BRDF Rendering

- Wave optics BRDF rendering

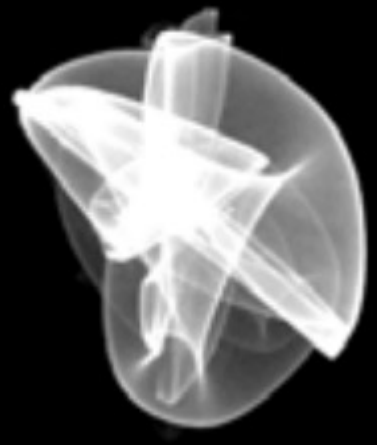


Design Custom BRDF with Wave Optics

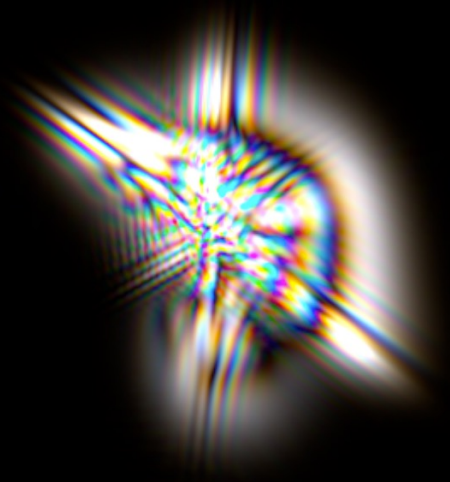
- Wave optics BRDF rendering



Surface Geometry



Geometric Optics



Wave Optics

[Yan et al. 2018]

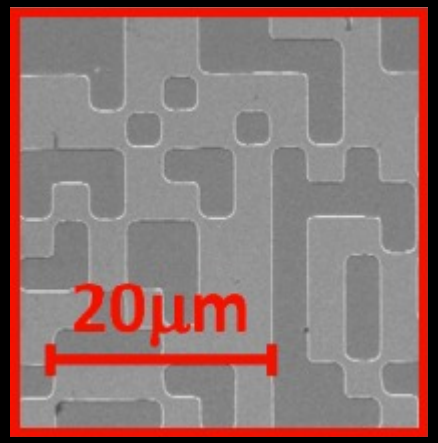
Design Custom BRDF with Wave Optics

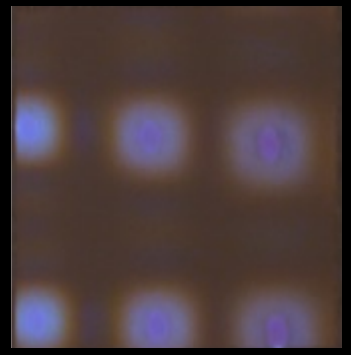
- Previous work in BRDF design with wave optics

Controls only shape

White light

500nm laser



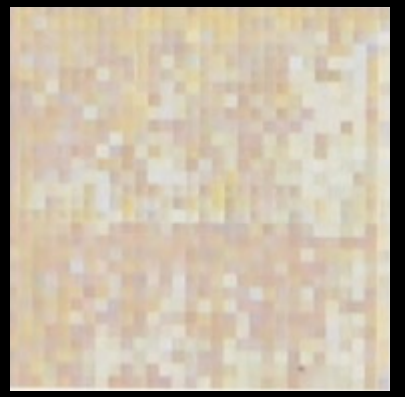


Surface Geometry

Reflectance

[Levin et al. 2013]

Controls only color



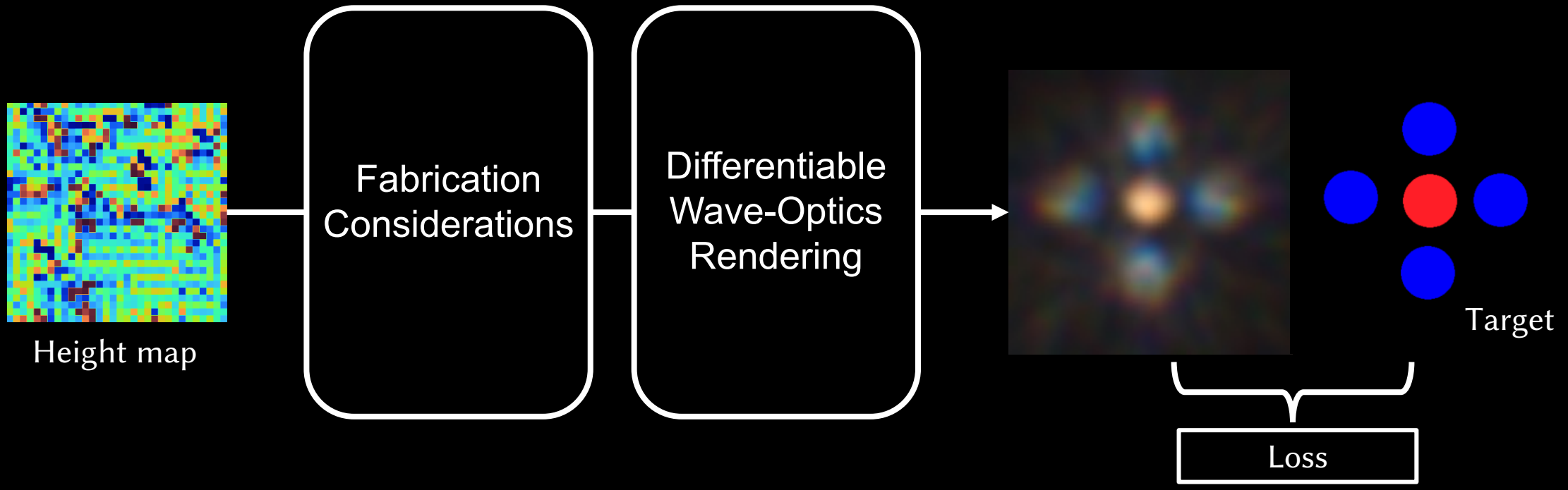
Surface Geometry

Reflectance

[Auzinger et al. 2018]

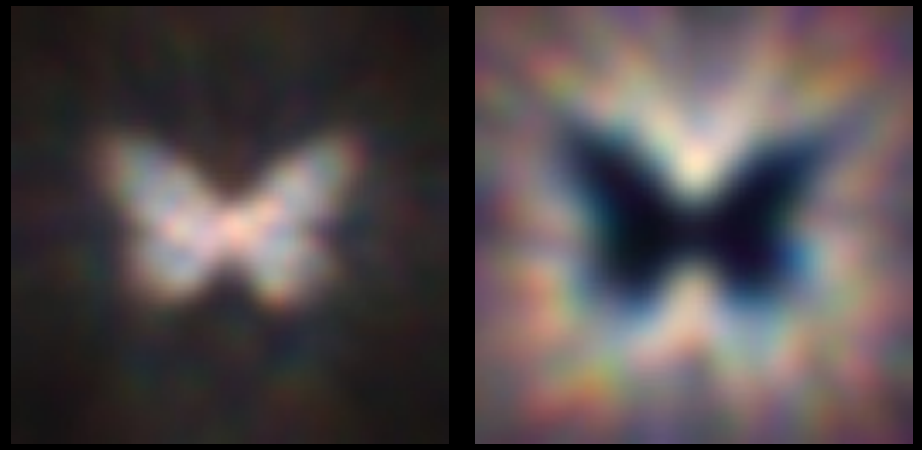
Overview

- Goal: control shape and color of BRDF at the same time
- Approach: fabrication-aware differentiable wave-optics method



Overview

- Contributions
  - Control the angular behavior of BRDF



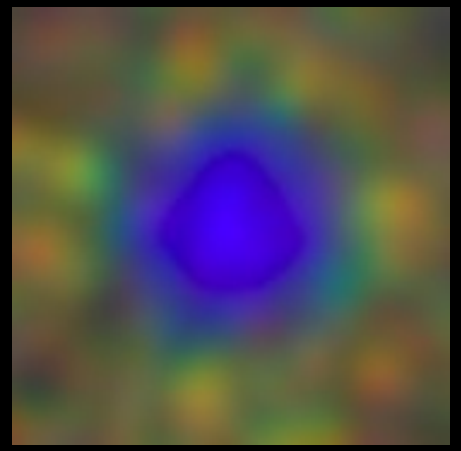
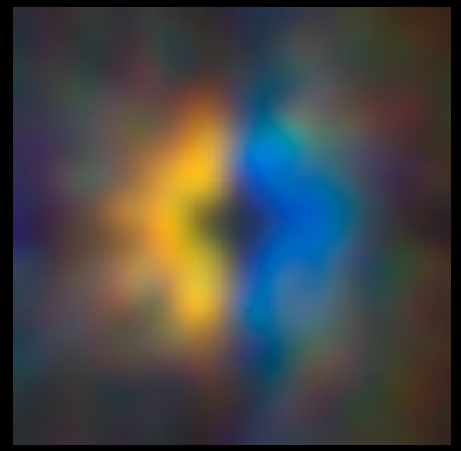
Overview

- Contributions
  - Control the angular behavior of BRDF
  - Controls the spectral behavior of BRDF

Overview

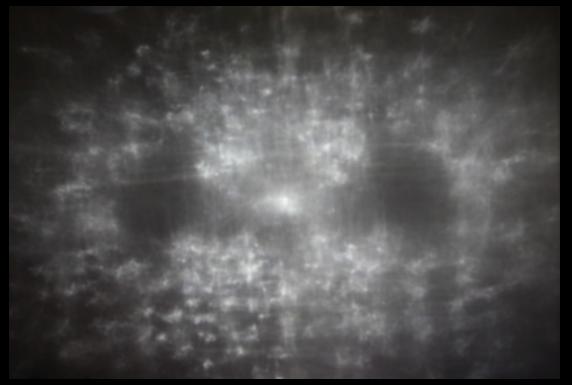
- Contributions
  - Control the angular behavior of BRDF
  - Controls the spectral behavior of BRDF
  - Control the angular + spectral behavior at the same time



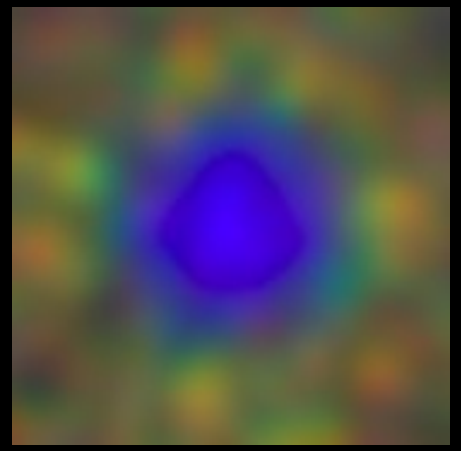
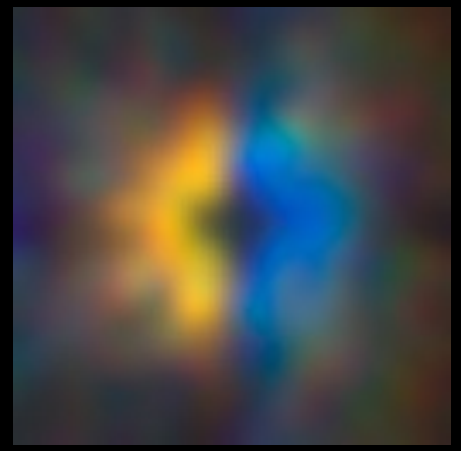
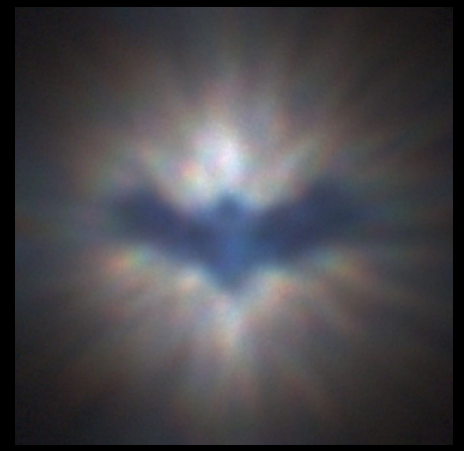
Overview

- Contributions
  - Control the angular behavior of BRDF
  - Controls the spectral behavior of BRDF
  - Control the angular + spectral behavior at the same time
  - Better quality in real fabrication



Weyrich et al. [2009]



Previous Work

Taxonomy

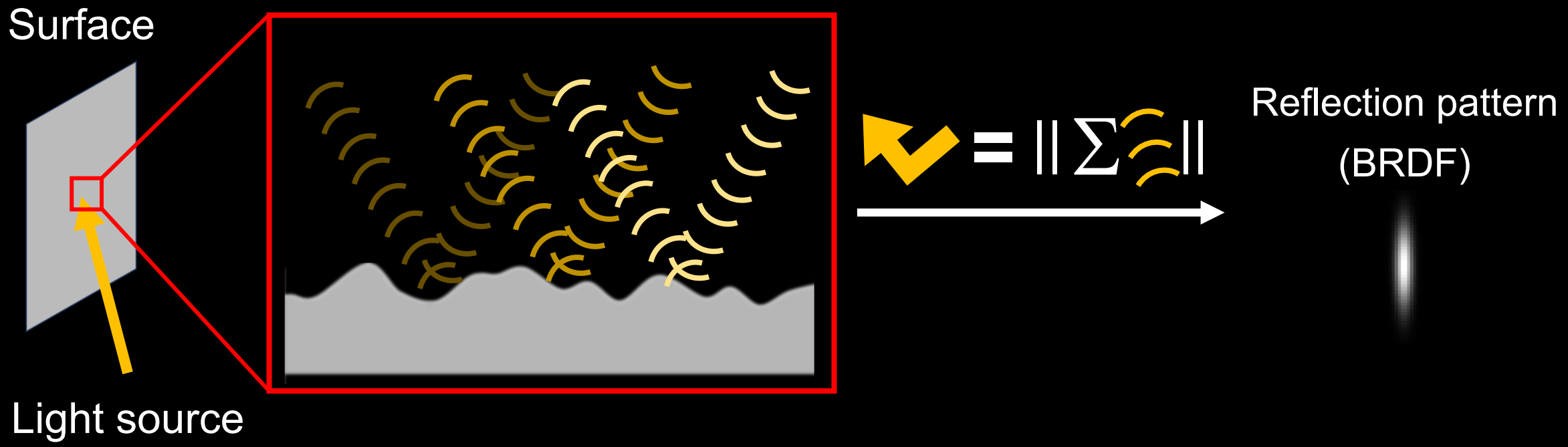
Wave-Optics Rendering

Material Fabrication

Structural Coloration

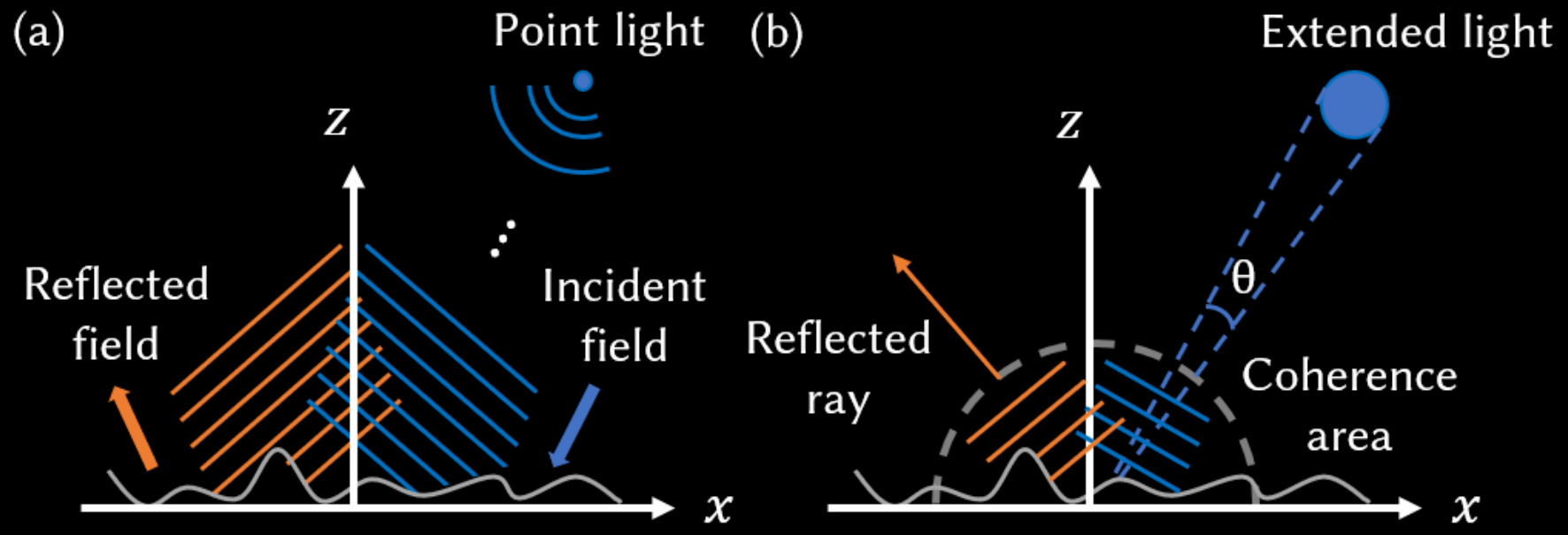
Wave-Optics Rendering

- Wave optics BRDF rendering



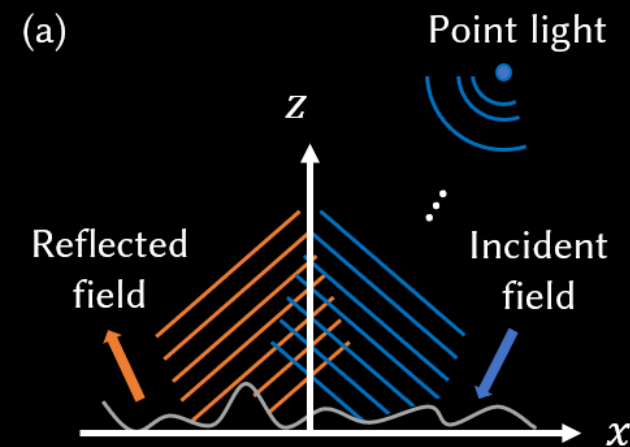
Wave-Optics Rendering

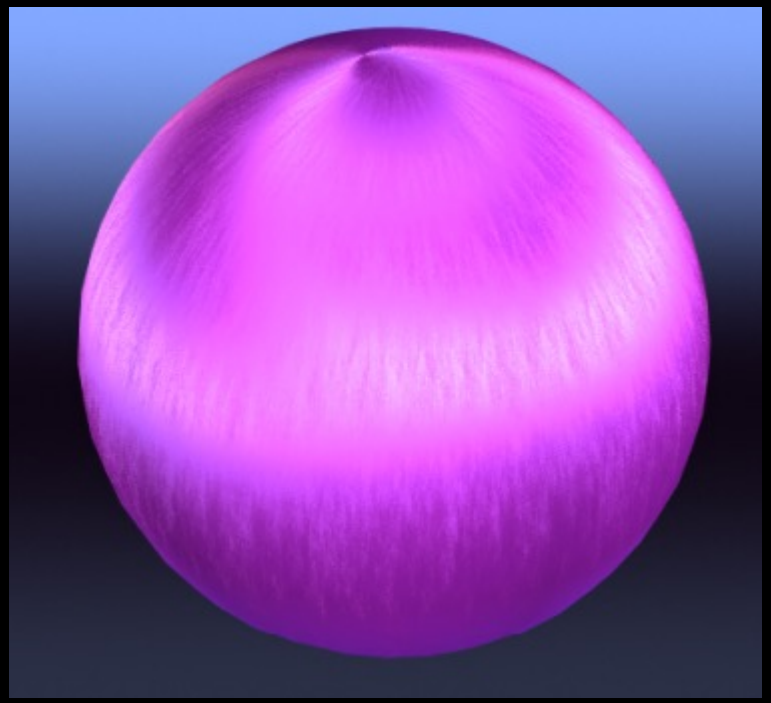
- Wave optics BRDF rendering



Wave-Optics Rendering

- Point light source



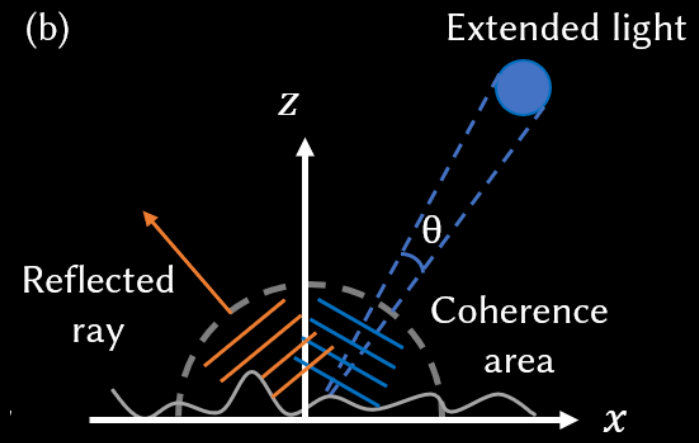


[Stam 1999]

[Low et al. 2012]

Wave-Optics Rendering

- Extended light source

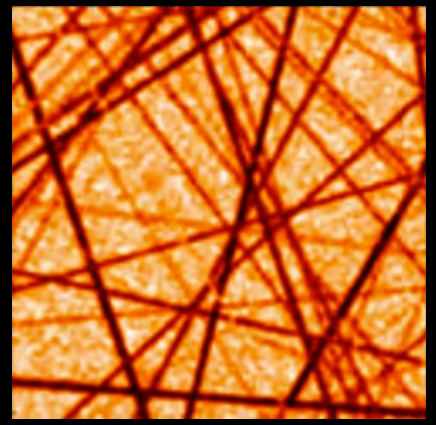


[Dhillon et al. 2014]

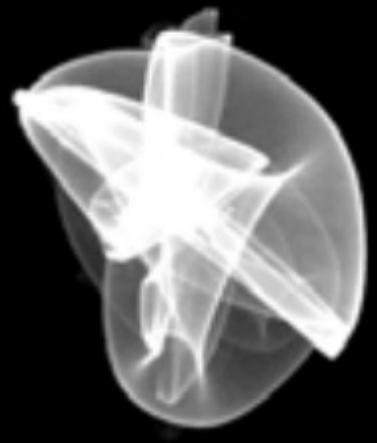
[Yan et al. 2018]

Wave-Optics Rendering

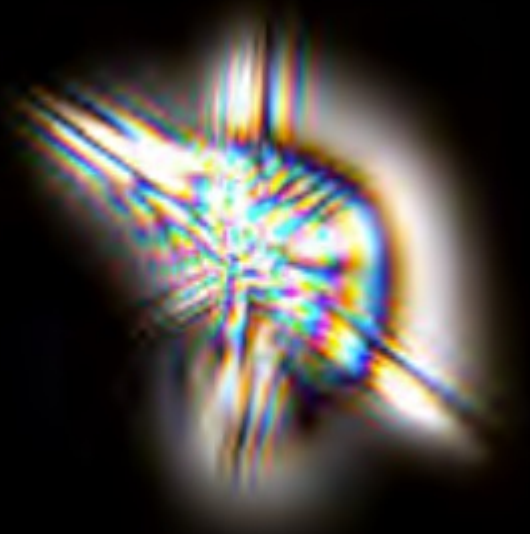
- Wave optics rendering can simulate color BRDF



Surface Geometry



Geometric Optics



Wave Optics

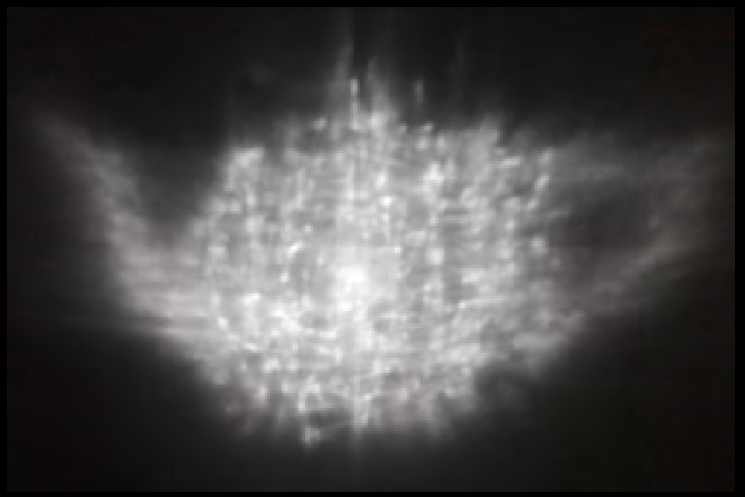
[Yan et al. 2018]

Material Fabrication

- Geometric

[Luongo et al. 2020

[Chermain et al. 2023]



[Weyrich et al. 2009]

Material Fabrication

- Wave optics

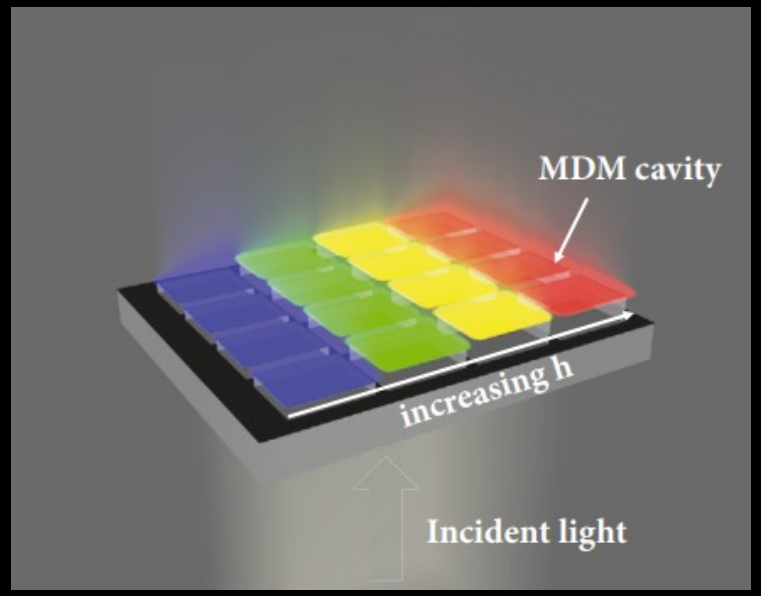
Vertical illumination

Horizontal illumination

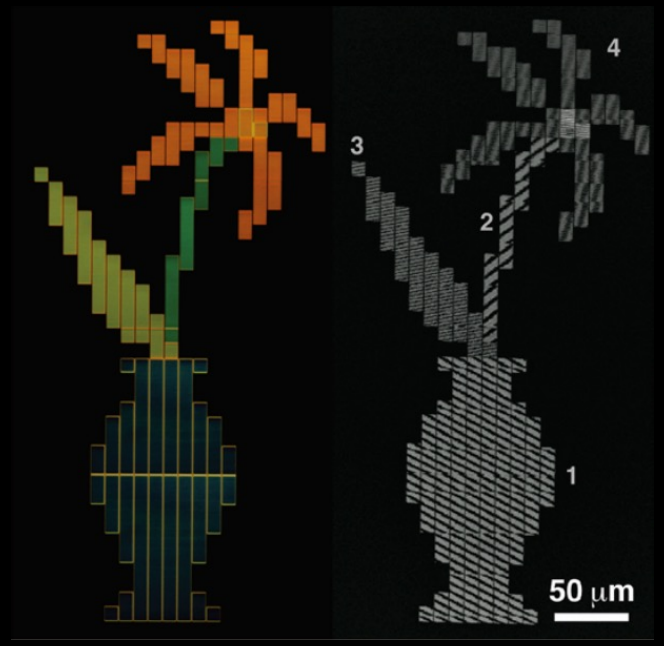
[Levin et al. 2013]

Structural Coloration

- Non-differentiable



[Wang et al. 2018]



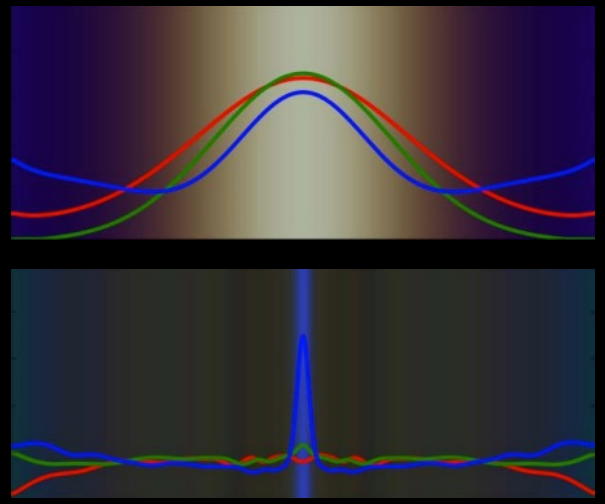
[Cao et al. 2010]

[Franklin et al. 2015]

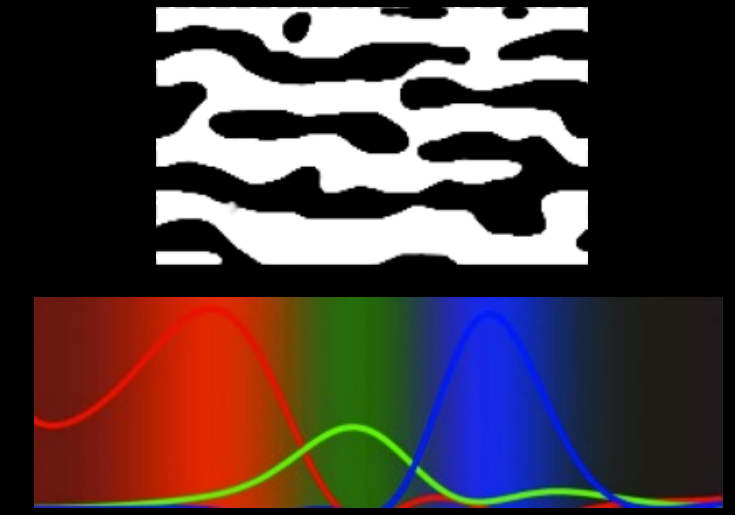
Structural Coloration

- Differentiable

[Auzinger et al. 2018]



[Johansen et al. 2014; 2015]



[Andkjær et al.2014]

Comparison

- Compared to previous work

	[Weyrich et al. 2009]	[Levin et al. 2013]	[Auzinger et al. 2018]	[Johansen et al. 2015]	[Andkjær et al. 2014]	**Ours**
Shape	√	×	×	×	√	√
Color	×	√	√	√	√	√
Manufacturability	√	√	√	√	×	√

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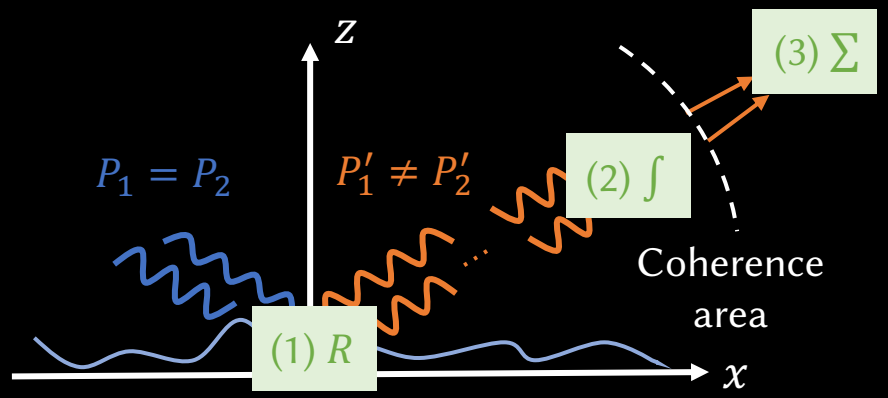
Method

Overview



Differentiable rendering pipeline

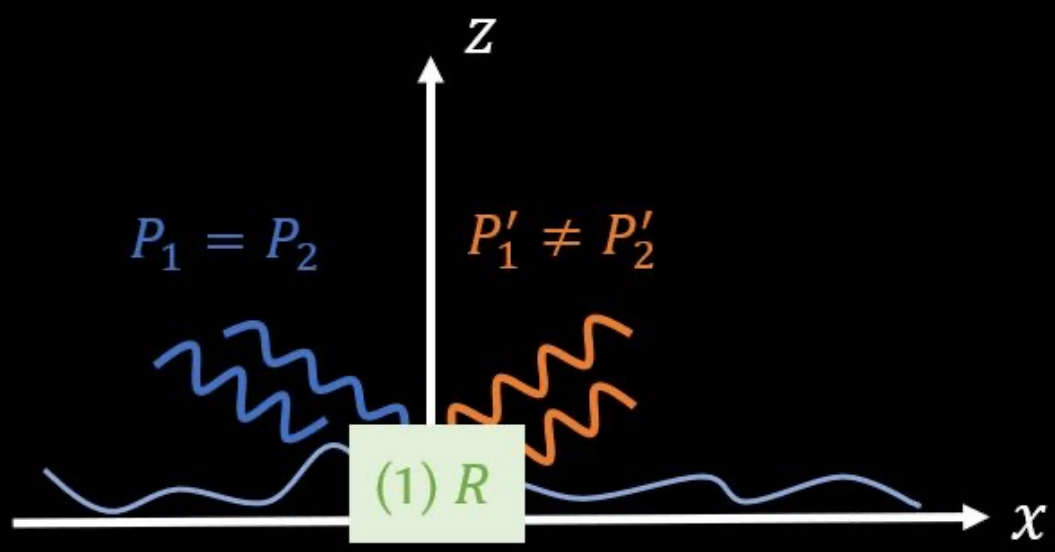
Noise modeling, height calibration, choice of parameters…

Real-fabrication consideration

Differentiable rendering

- Differentiable rendering
  - Step1: Surface geometry and modulation (replace equation later)

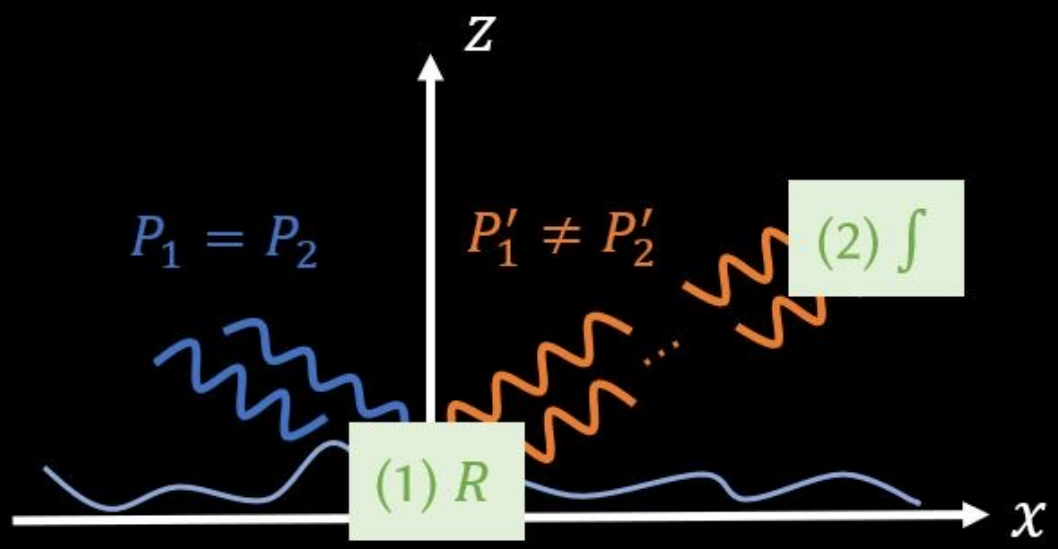
$$R(\boldsymbol{s}) = \exp(-i\frac{2\pi}{\lambda}\xi_1 H(\boldsymbol{s}))$$



Differentiable rendering

- Differentiable rendering
  - Step1: Surface geometry and modulation
  - Step2: Fourier transform

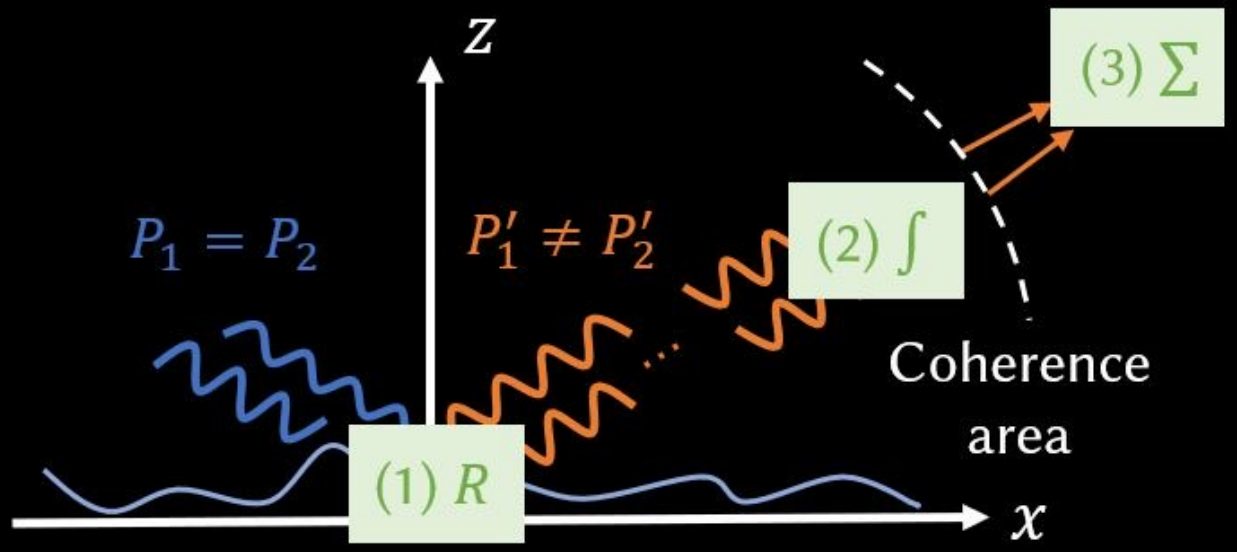
$$\mathcal{F}[R]\left(\frac{\bar{\boldsymbol{\psi}}}{\lambda}\right) = \int_{\bar{S}_c} R(\boldsymbol{s}) \exp\left(-i\frac{2\pi}{\lambda}(\bar{\boldsymbol{\psi}} \cdot \boldsymbol{s})\right) d\boldsymbol{s}$$



Differentiable rendering

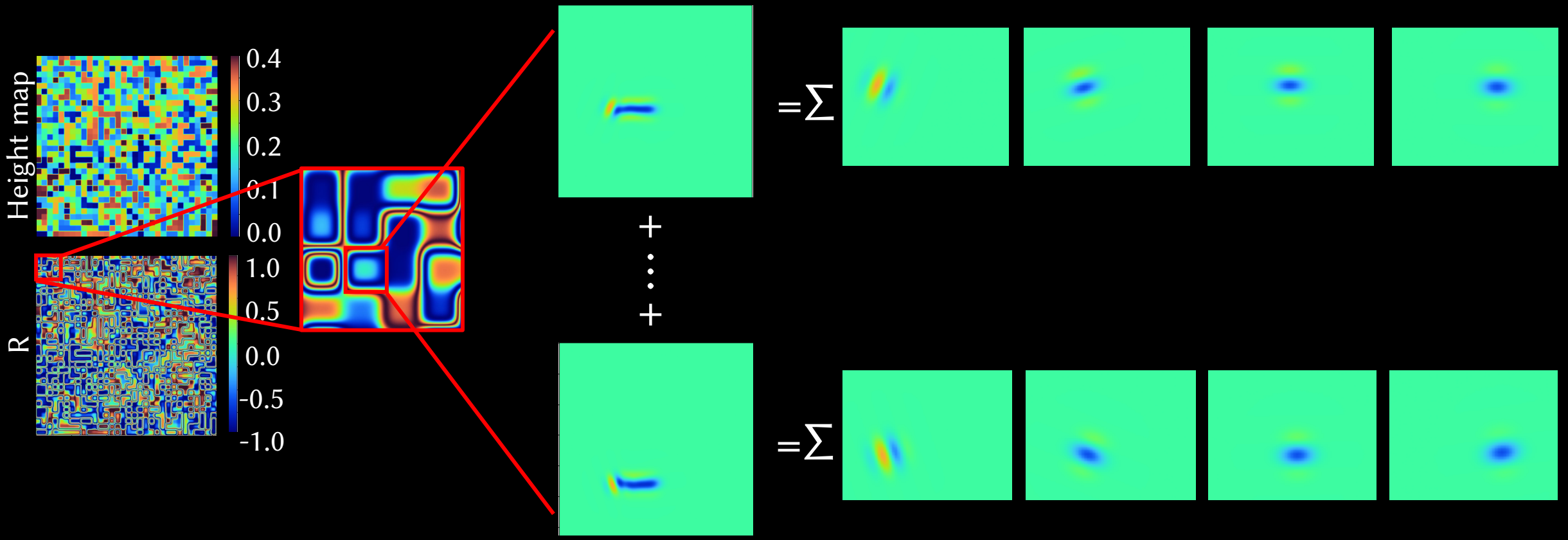
- Differentiable rendering
  - Step1: Surface geometry and modulation
  - Step2: Fourier transform
  - Step3: Coherence area integration

$$f_r(\boldsymbol{\omega}_i, \boldsymbol{\omega}_o; \lambda) = \frac{\xi_1}{A_c} \left| \mathcal{F}[R^*]\left(\frac{\bar{\psi}}{\lambda}\right) \right|^2$$



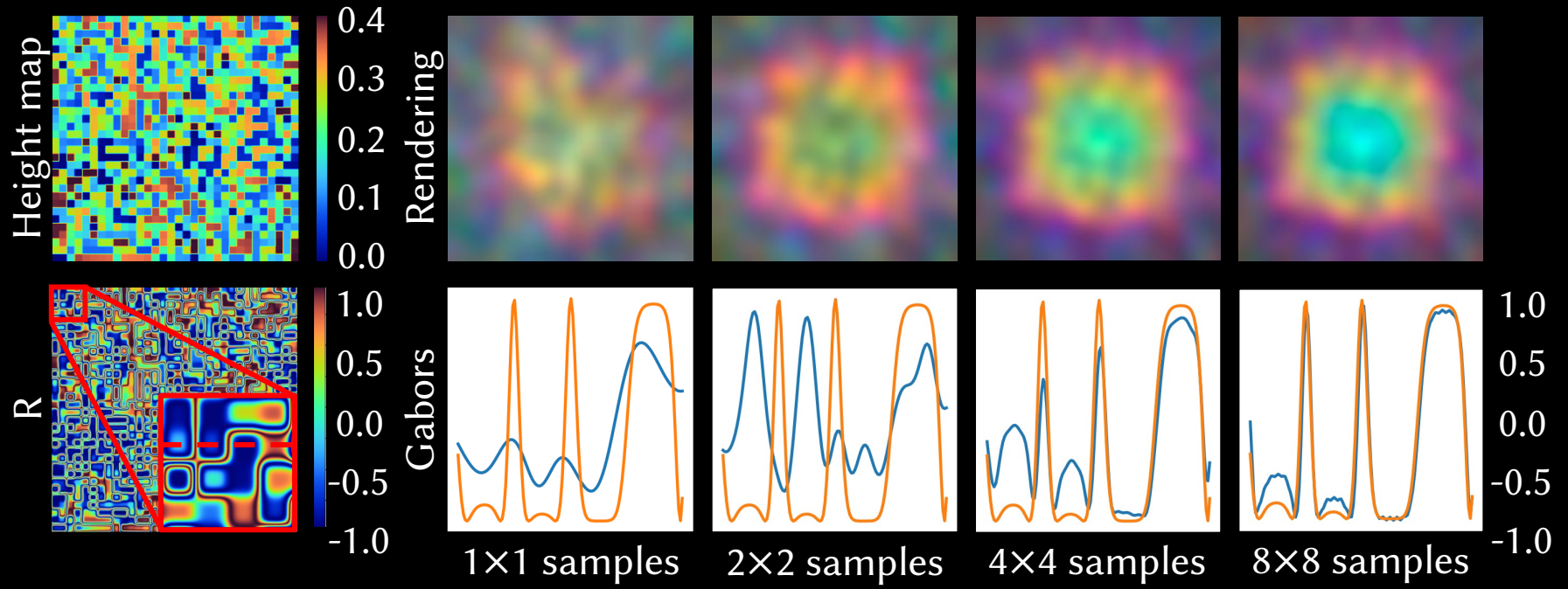
Differentiable rendering

- Gabor decomposition
  - Description: decompose R map into ΣG



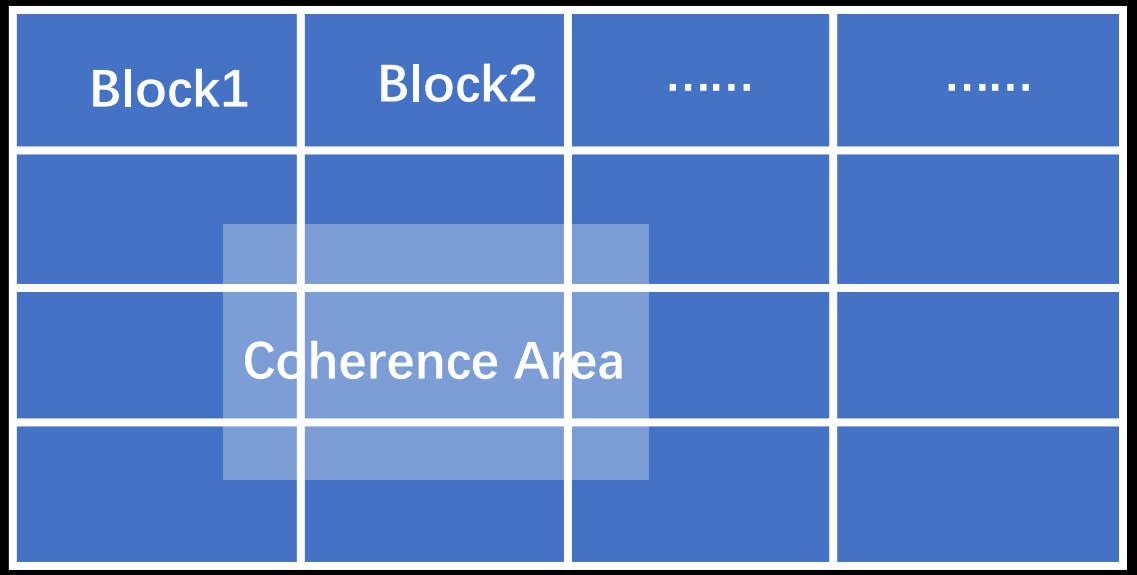
Differentiable rendering

- Gabor decomposition
  - Description: sampling



Differentiable rendering

- Gabor decomposition:
  - Description
  - Memory-Efficient Backward Propagation:



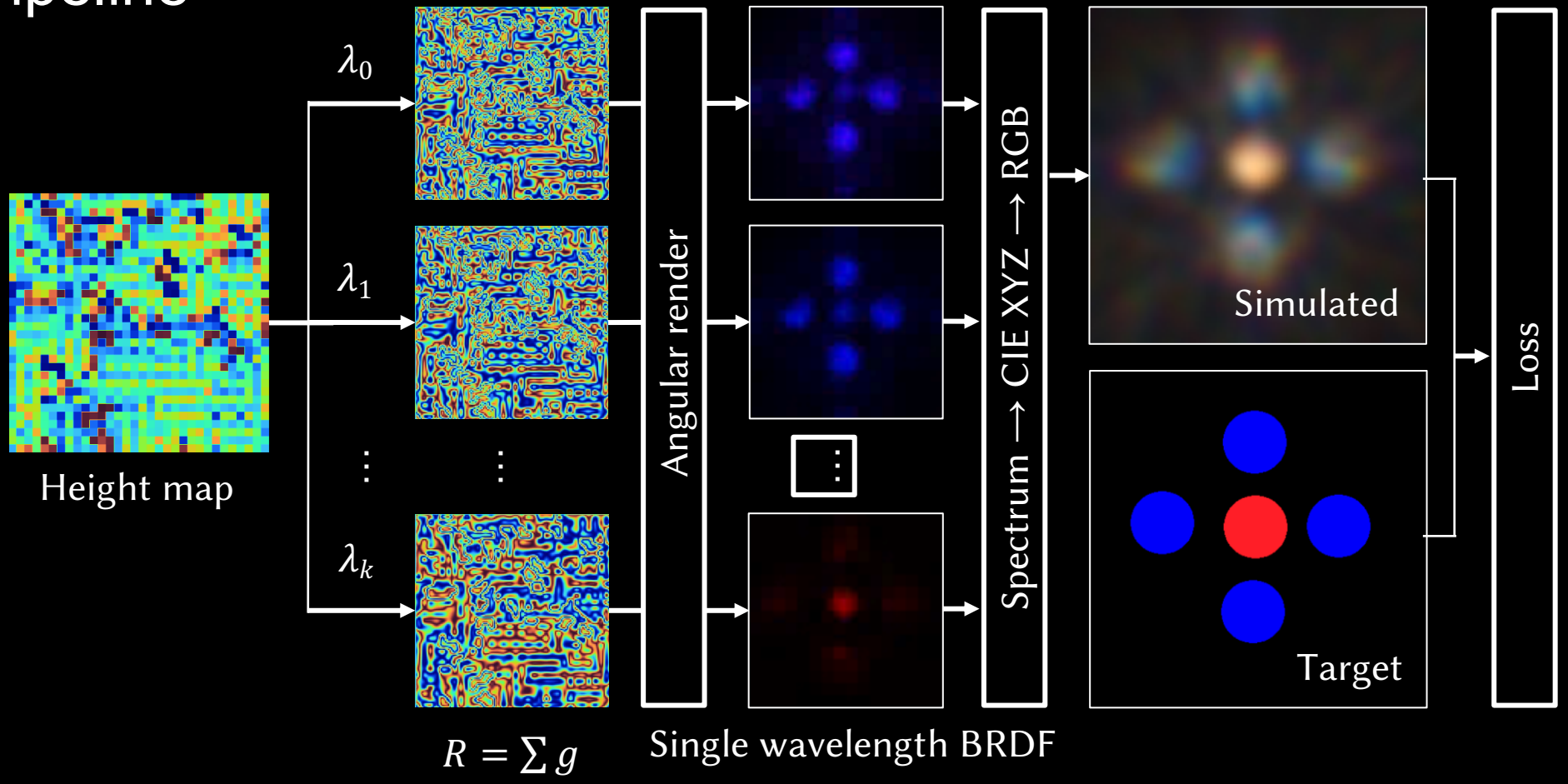
Differentiable rendering

- Gabor decomposition:
  - Description
  - Memory-Efficient Backward Propagation

	[Yu et al. 2009]	[Levin et al. 2013]	[Yan et al. 2018]	[Yan et al. 2018]	**Ours**
Speed (hours)	819.2	2.6	16.0	9.6	**1.3**
Memory (GB)	0.59×4	10.7	-	16.1	**0.49**
Device	GPU	GPU	CPU	GPU	**GPU**

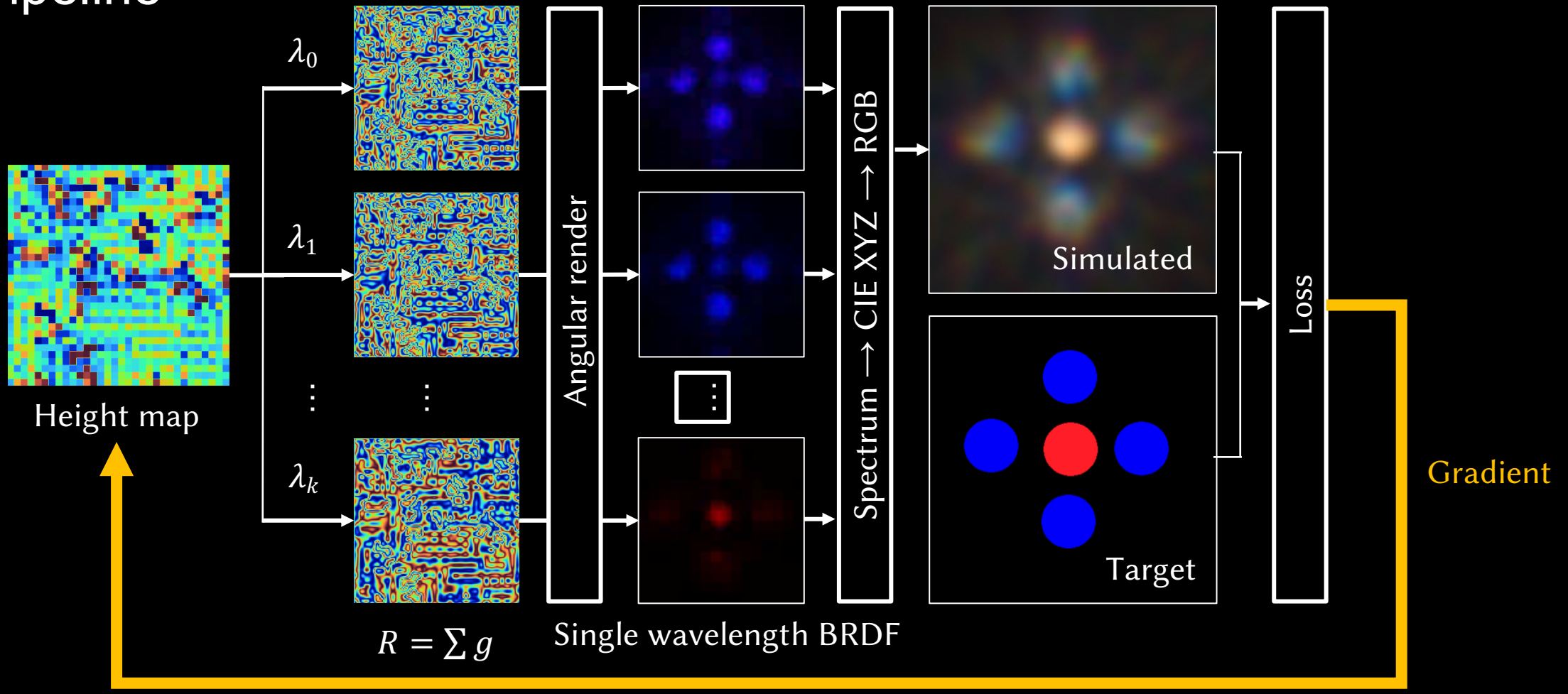
Differentiable rendering

- Pipeline



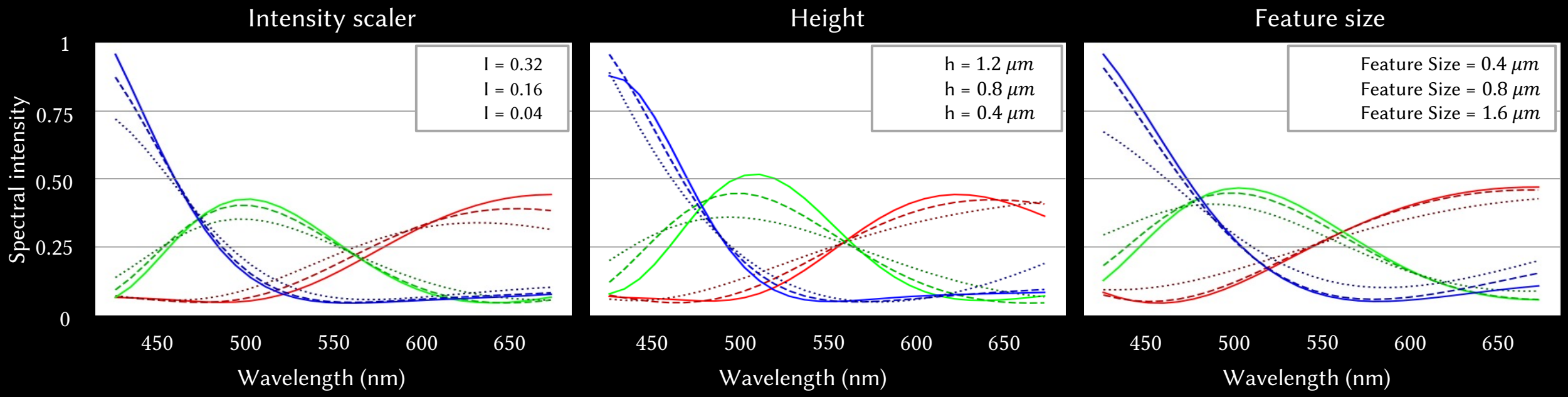
Differentiable rendering

- Pipeline



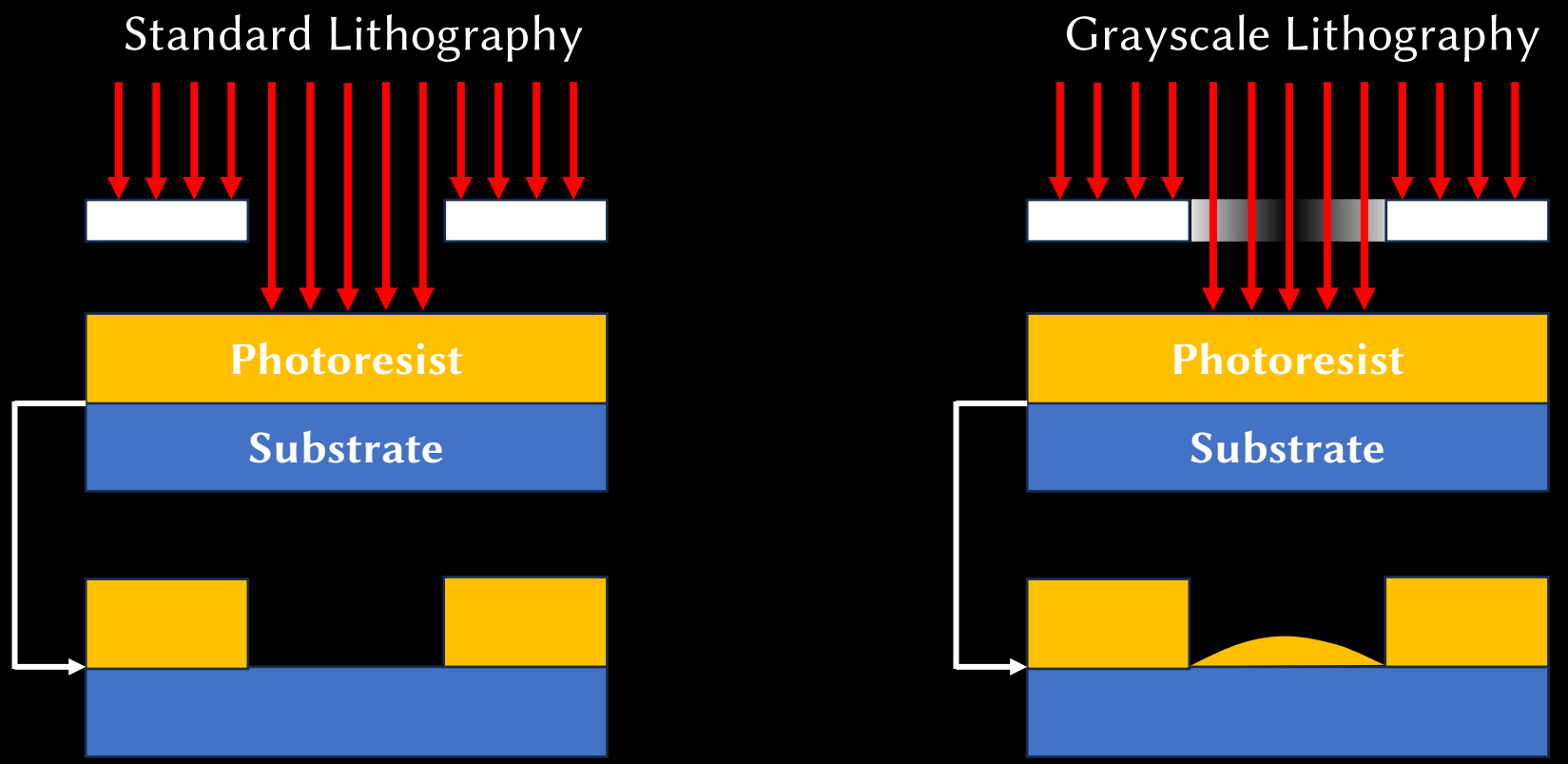
Fabrication

- Parameter consideration



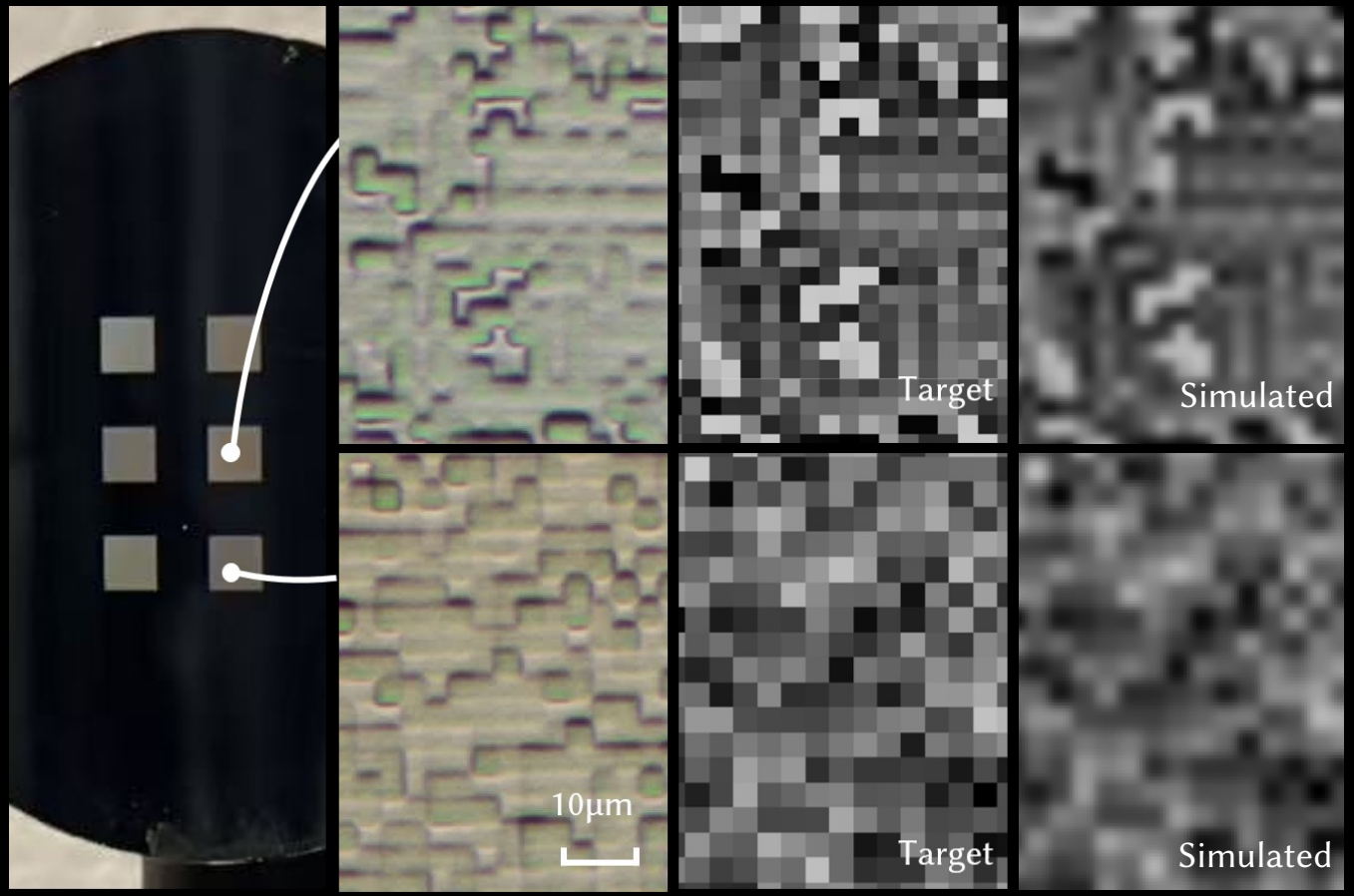
Fabrication

- Multi-pass binary vs. Grayscale lithography



Fabrication

- Noise and blur



Before

After

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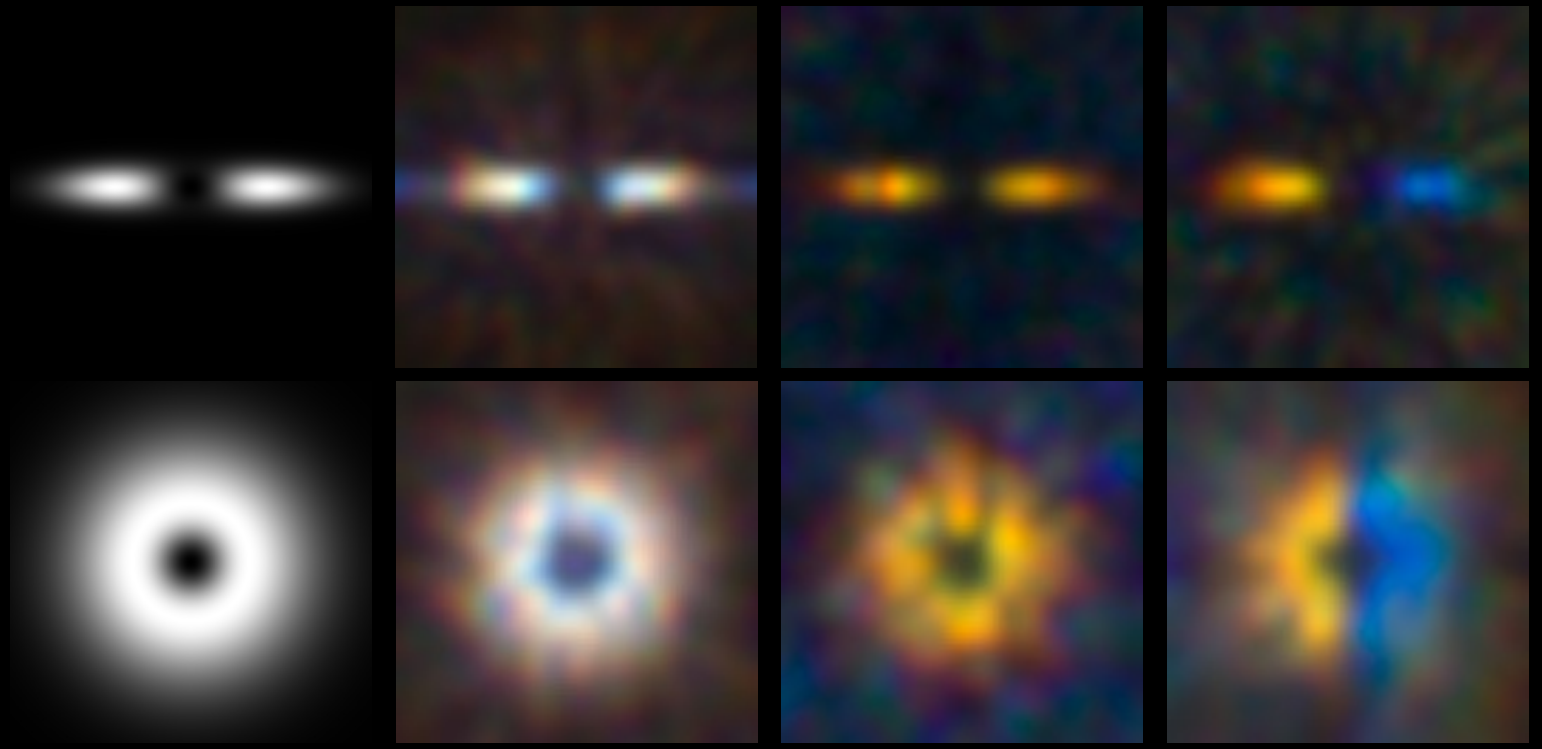
Results

Training

- Training workstation
  - Dual AMD EPYC 7763 CPUs
  - 768GB DDR4 memory
  - Single NVIDIA GeForce RTX 4090 GPU
- Training time: 6--12 hours

Results (simulation)

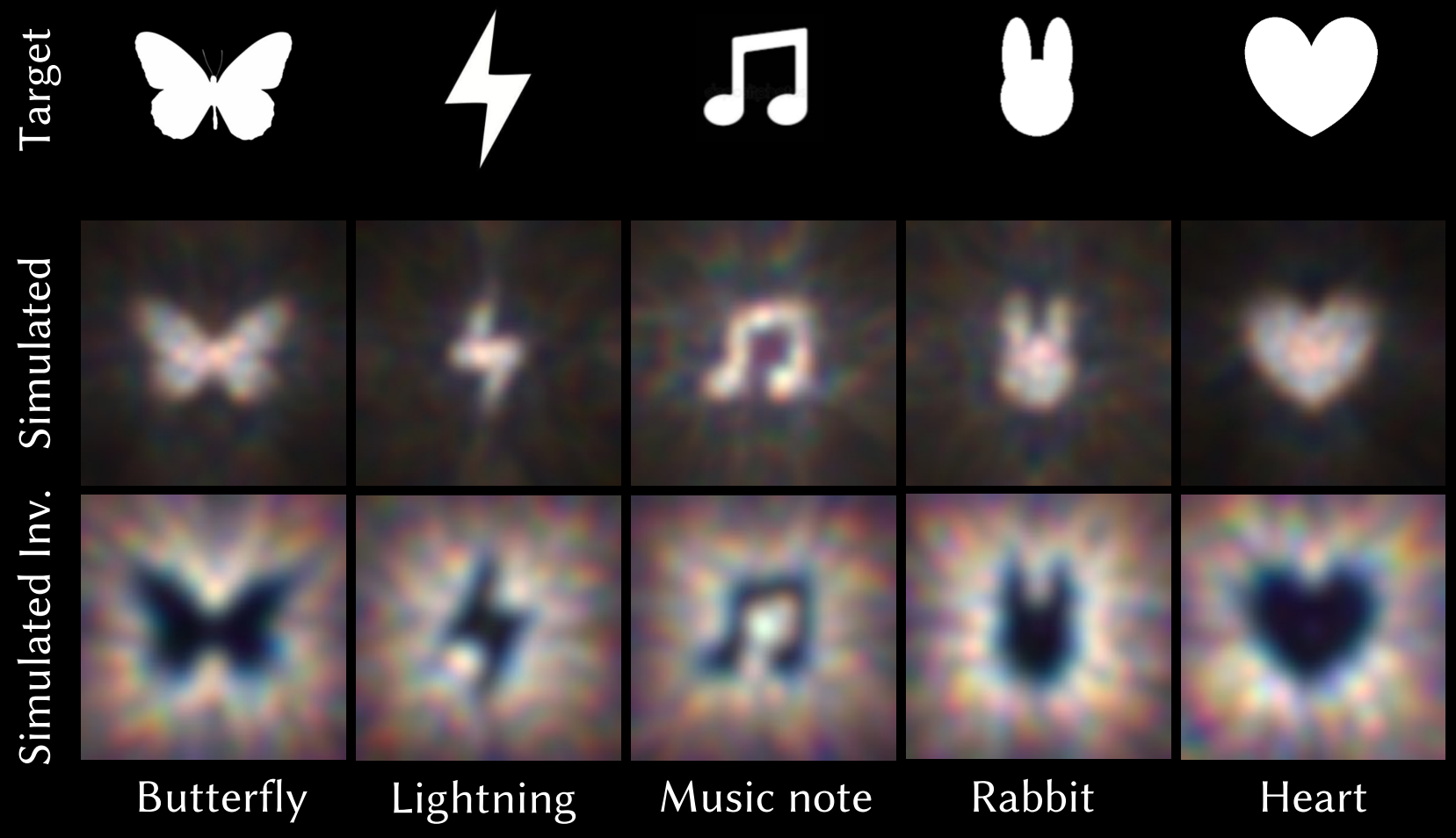
- Anti-mirror



Target White Red Iridescent

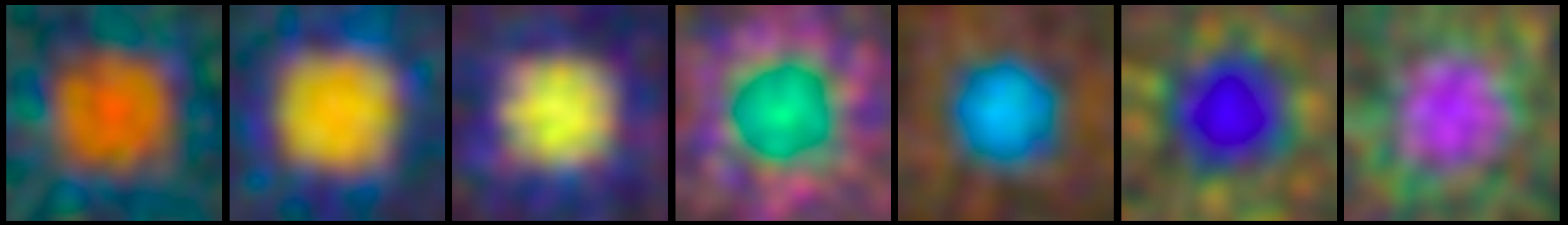
Results (simulation)

- Pictorial

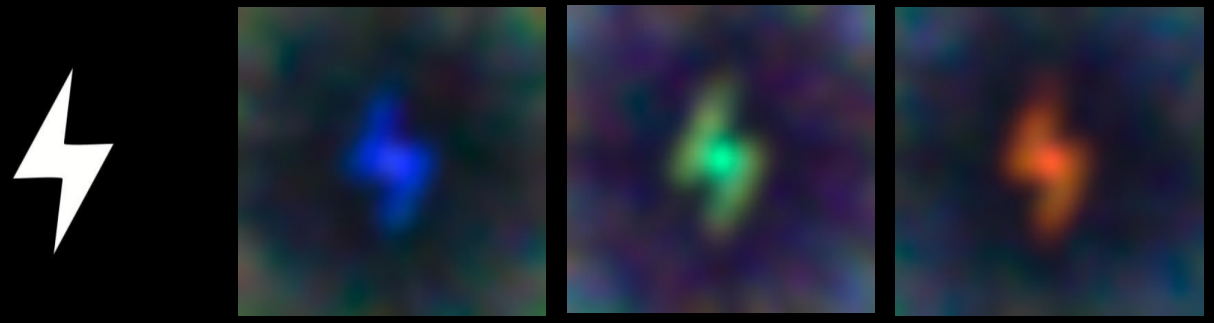


Results (simulation)

- Structural color and colored pictorial



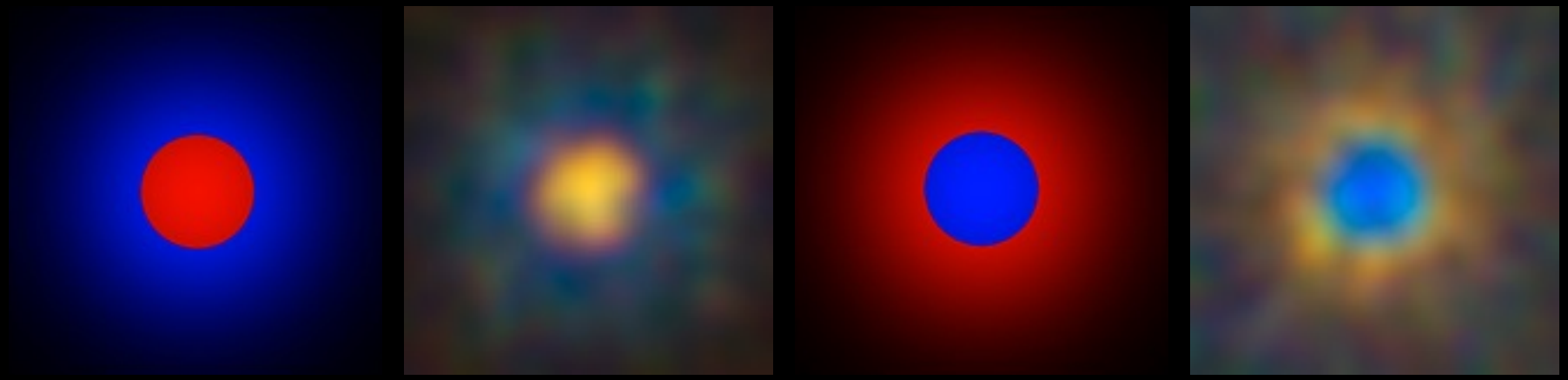
Red Orange Yellow Green Cyan Blue Purple



Lightning Blue Green Red

Results (simulation)

- Iridescent



Target Simulated Target Simulated

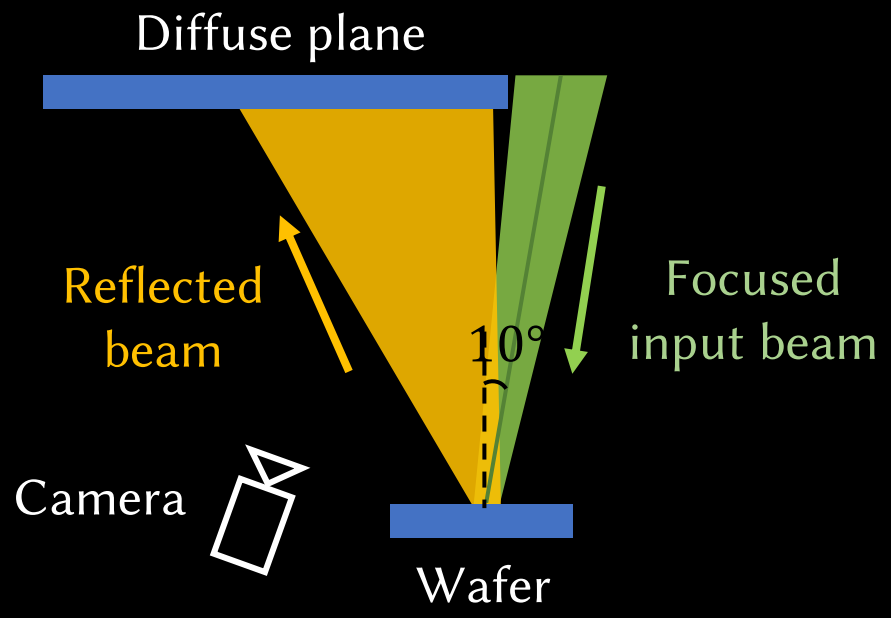
Iridescent Circle Circle Inverted

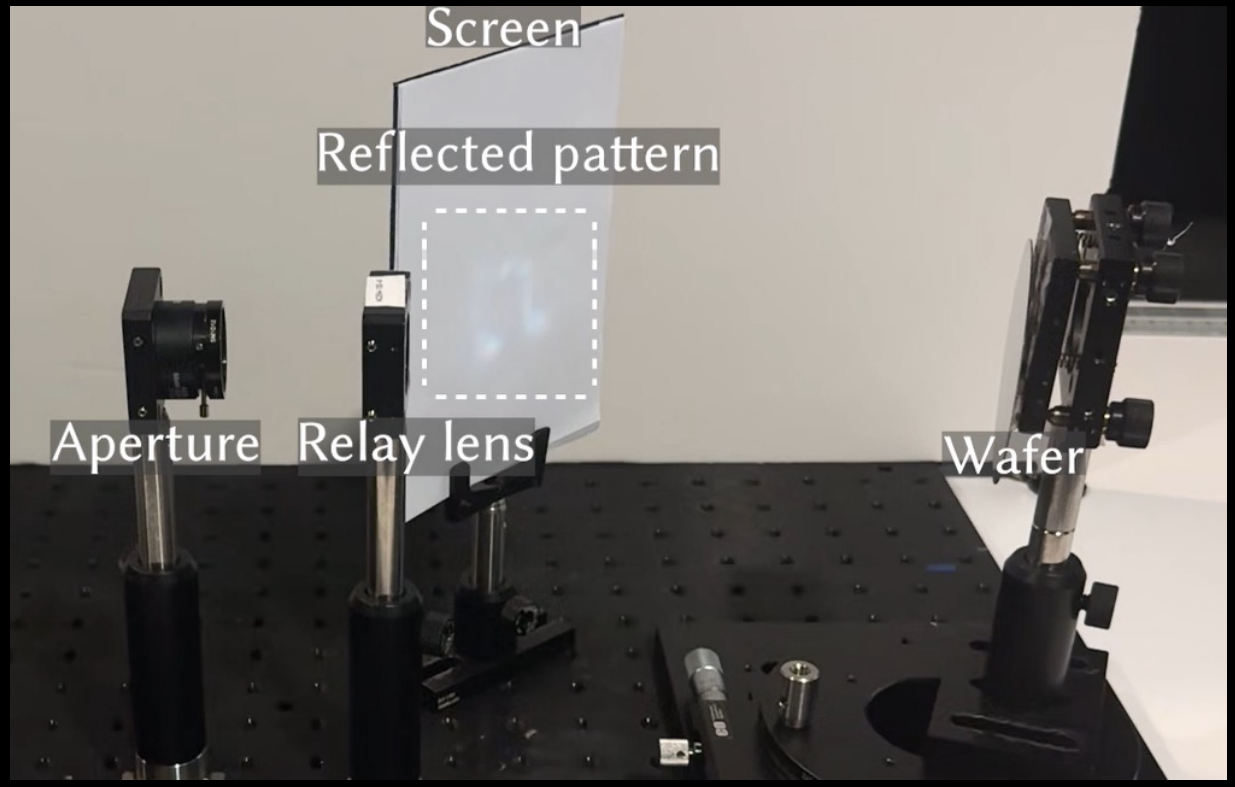
Results (fabrication)

- Fabrication
  - Heidelberg DWL66+ laser writer, equipped with a 5 mm write head.
  - AZ 4562 photoresist.
  - A 50nm aluminum layer is deposited using an ESC Ion Beam Assist Sputter system (model ESCRD4).
- Height range: 0--0.8μm
- Feature size: 1.5 or 2 μm

Results (fabrication)

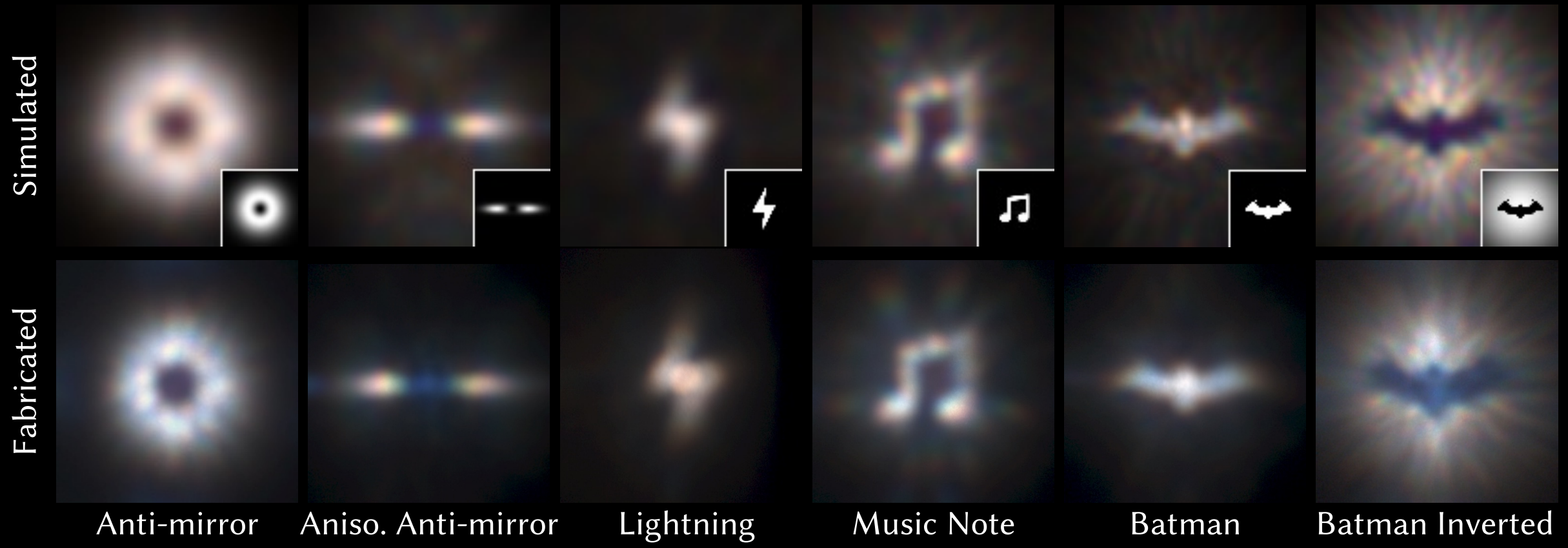
- Capture setup





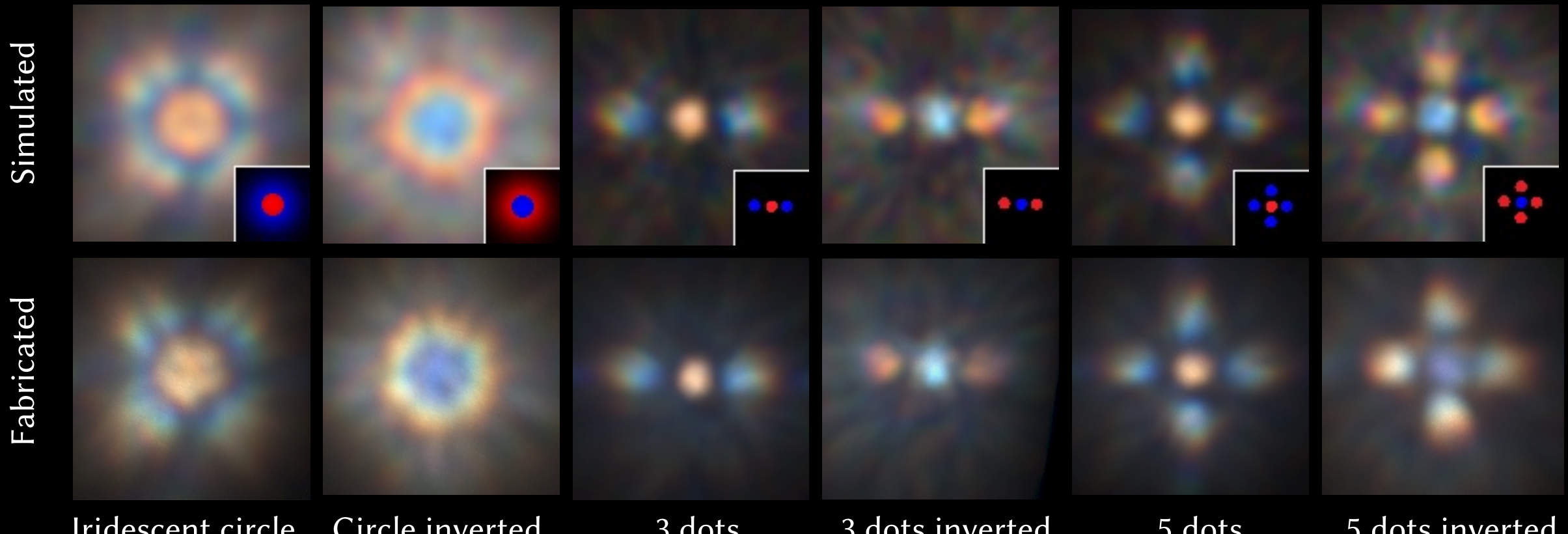
Results (fabrication)

- Capture setup
- Results



Results (fabrication)

- Capture setup
- Results



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Conclusion

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- Our work introduces a differentiable wave-optics rendering pipeline for BRDF design, enabling colored BRDF fabrication

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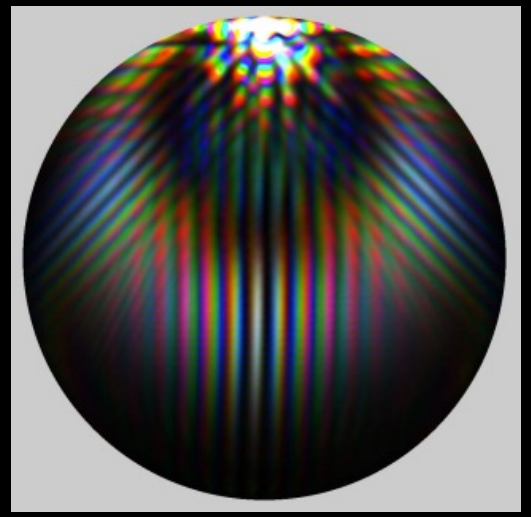
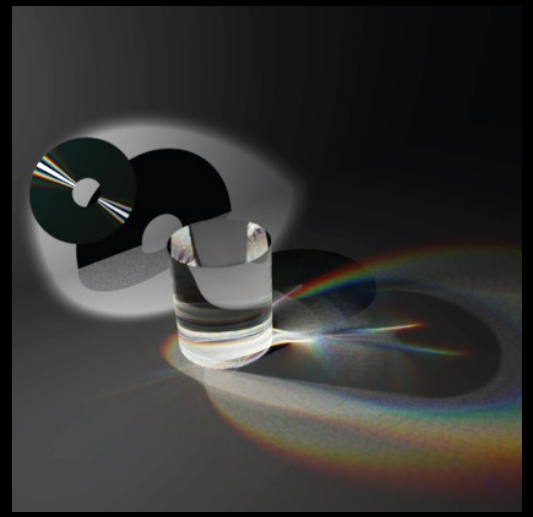
- Our work introduces a differentiable wave-optics rendering pipeline for BRDF design, enabling colored BRDF fabrication
- Limitations
  - Assume a globally planar surface
  - Ignores shadowing and masking effects
  - Constrained by the resolution and variability of grayscale lithography

Future work

- Incorporating advanced wave-optics frameworks
  - Non-planar
  - Shadowing and masking
  - Far-field diffraction and other light-field effects



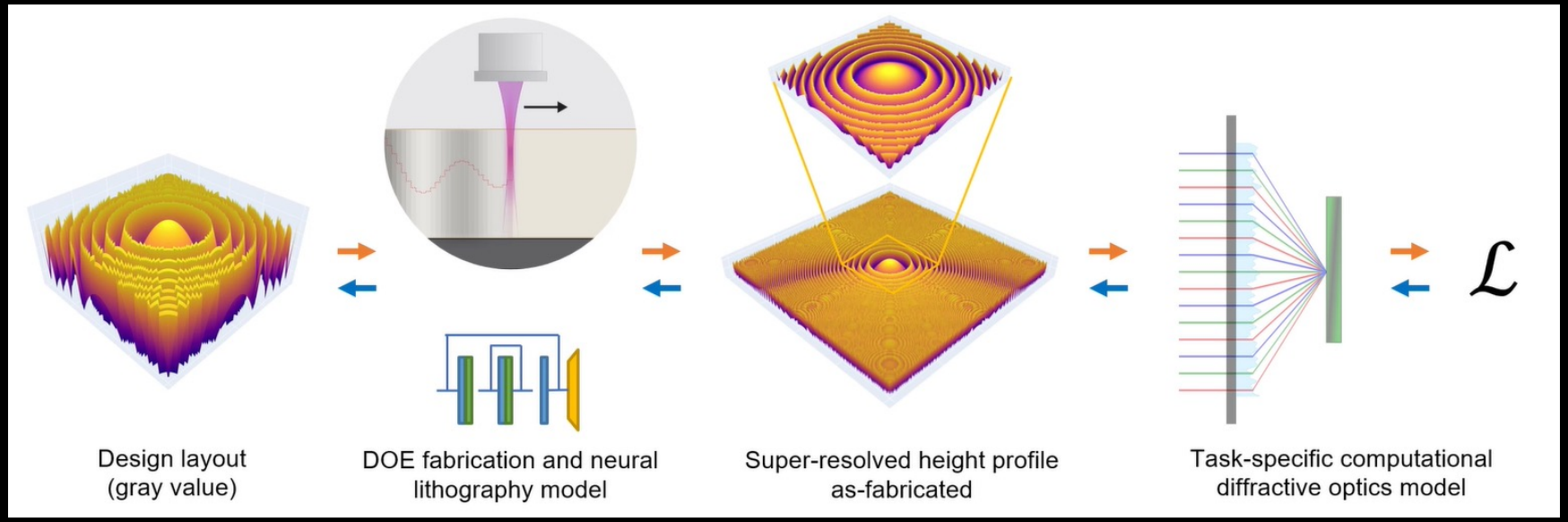
[Yu et al. 2023]



[Cuypers et al. 2012]

Future work

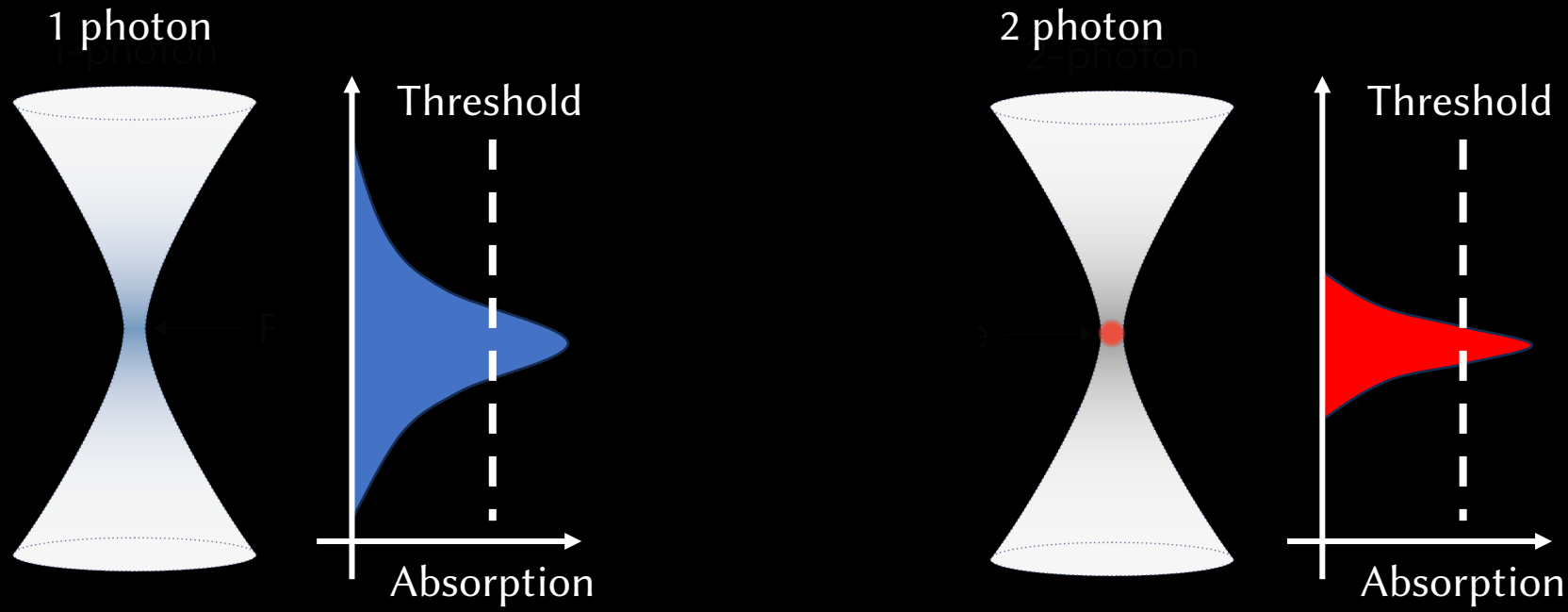
- Incorporating advanced wave-optics frameworks
- Modeling the lithography process directly as part of the optimization loop



[Wei et al. 2025]

Future work

- Incorporating advanced wave-optics frameworks
- Modeling the lithography process
- Improved fabrication technologies, like two-photon lithography



Thank you

- Find code and data in our project page

https://vclab.kaist.ac.kr/siggraphasia2025p1/

https://github.com/KAIST-VCLAB/color-brdfs-with-wave-optics