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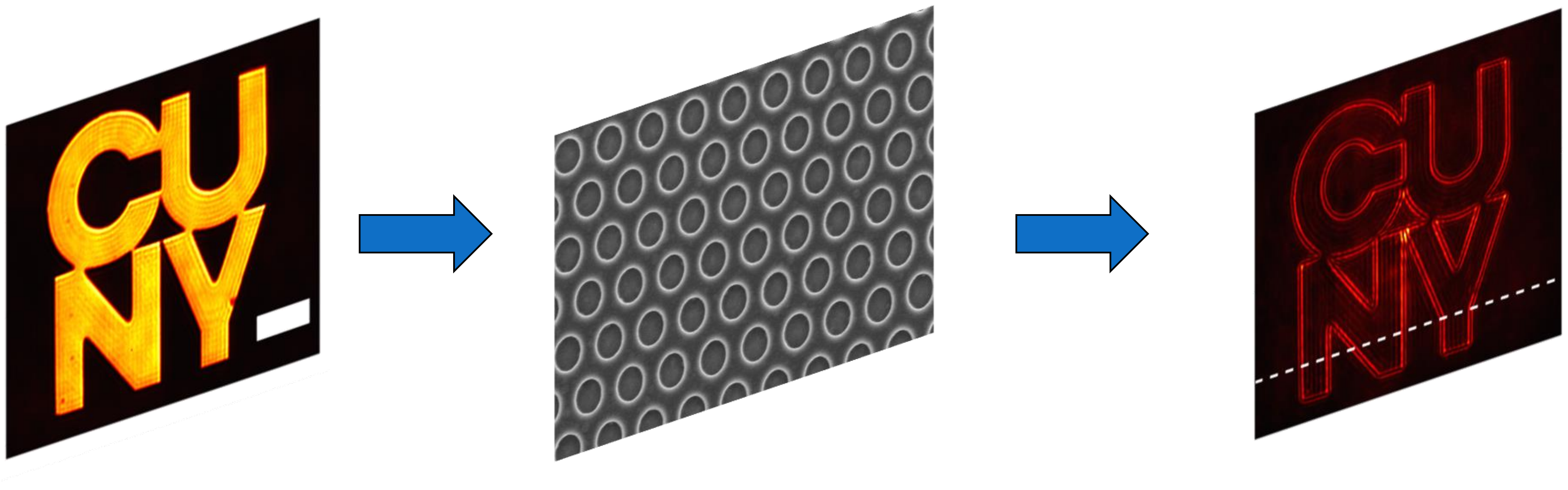
Analog Image Processing with Metamaterials

Michele Cotrufo, Advanced Science Research Center (CUNY), New York



OUTLINE

1. Introduction

- Why do we need analog computing and image processing?
- How can metamaterials and metasurfaces perform image processing?

2. Spatial Image Processing: State of the art and Main challenges

- What are the different approaches used?
- Which figures of merit we need to improve to go from proof-of-principles to useful devices?
- How to overcome the need for coherent illumination?

3. What's next?

- Spatio-temporal image processing
- More complex mathematical operations
- Reconfigurable devices

4. (Open) Discussion

- Beyond the hype: What are (if any) the <u>real</u> benefits of metasurfaces in image processing?
- Are metasurface-based image-processing devices always worth the effort?

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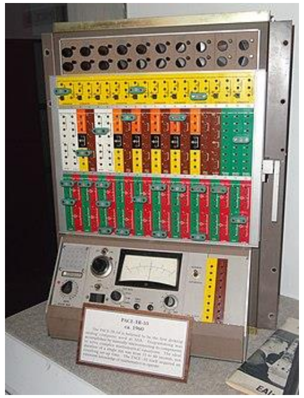
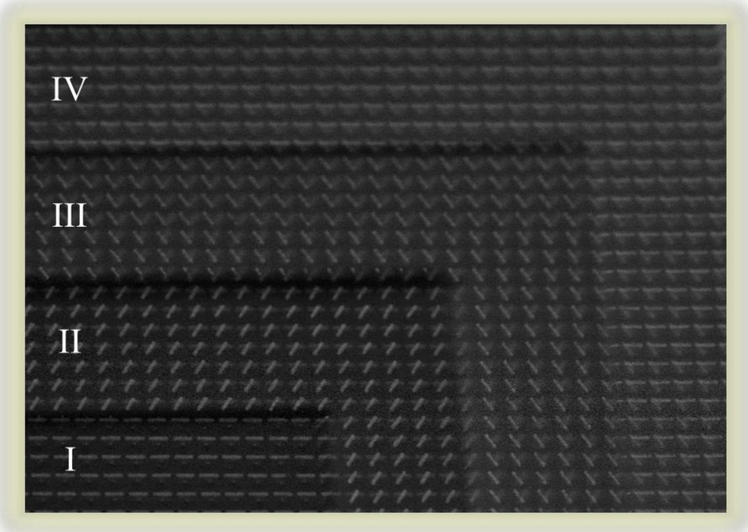
Digital vs. Analog Computing

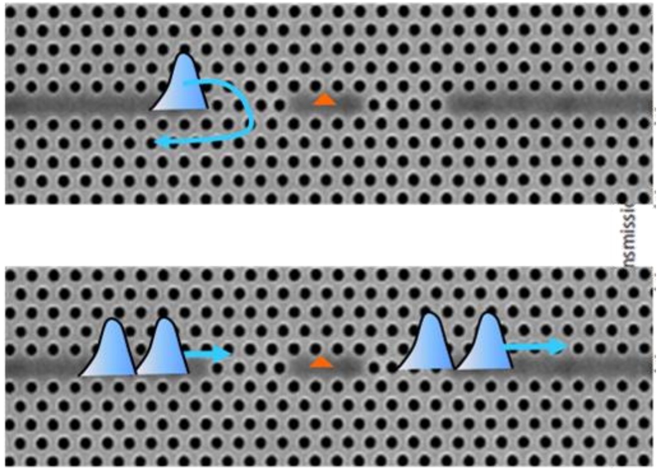


Valve body of an automatic transmission
Hydraulic Analog Computer

- Digital computers dominate our world, from data centers to personal computers, cell phones…
- They also require enormous amounts of power. ***Information processing and communications consume >10% of total energy in the US, and growing…***
- On average a single Google search produces ***0.2-0.3 grams of CO_2 emissions***
- Analog computers use continuous variations of a physical quantity to process signals – typically electrical, mechanical or hydraulic quantities.
- Their use faded out because of sensitivity to noise and other non-idealities.
- ***Today there is renewed interest (neuromorphic computing, hardware acceleration…), especially because of improved nanofabrication skills***

Using Light for Analog Computing





- Light is ***ubiquitous***, and ***cheap***
- We have learned how to control it very accurately ***at the nanoscale*** using ***photonic crystals*** and ***metamaterials***
- Light provides an ideal platform for ***ultrafast***, ***ultralow-energy*** signal processing and analog computing

USING LIGHT FOR ANALOG COMPUTING

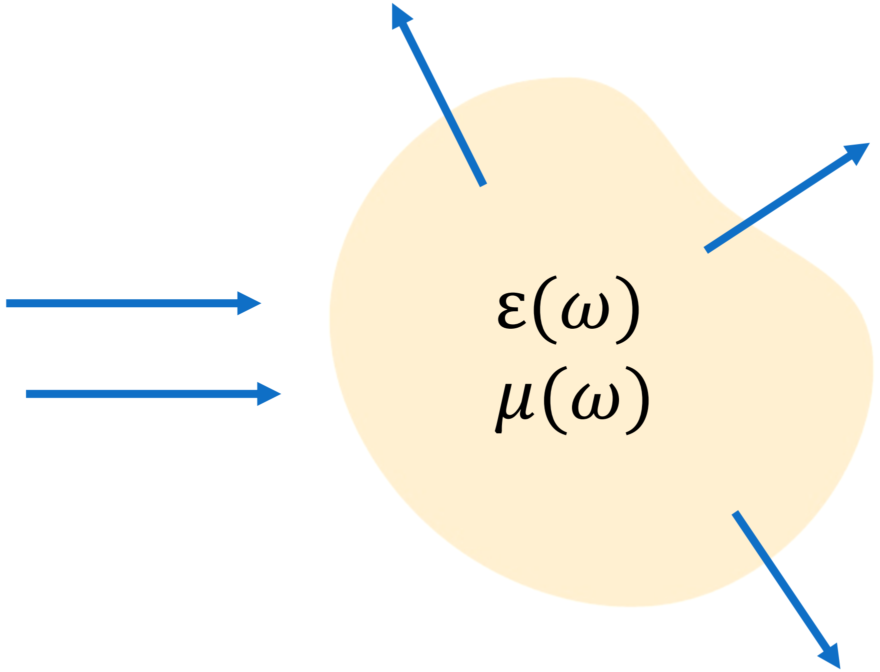
$f_{\text{in}}(x, y, t, \dots) \rightarrow \boldsymbol{E}_{\text{in}}(r, t)e^{i\omega_0 t}$

$\boldsymbol{E}_{\text{out}}(r, t)e^{i\omega_0 t} \rightarrow f_{\text{out}}(x, y, t, \dots)$

- Light is ***ubiquitous***, and ***cheap***
- We have learned how to control it very accurately ***at the nanoscale*** using ***photonic crystals*** and ***metamaterials***
- Light provides an ideal platform for ***ultrafast***, ***ultralow-energy*** signal processing and analog computing

ELECTROMAGNETIC METAMATERIALS

Meta (from the Greek, "beyond")-**Material**

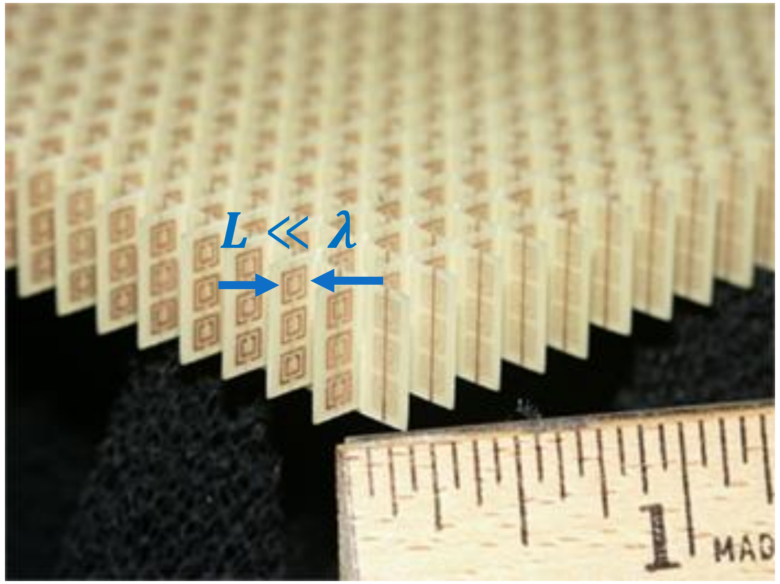


"Natural" materials

<u>Limited sets of material properties:</u>

- Refractive Index
- Frequency-Dependence
- Chirality
- Bianisotropy

- ....

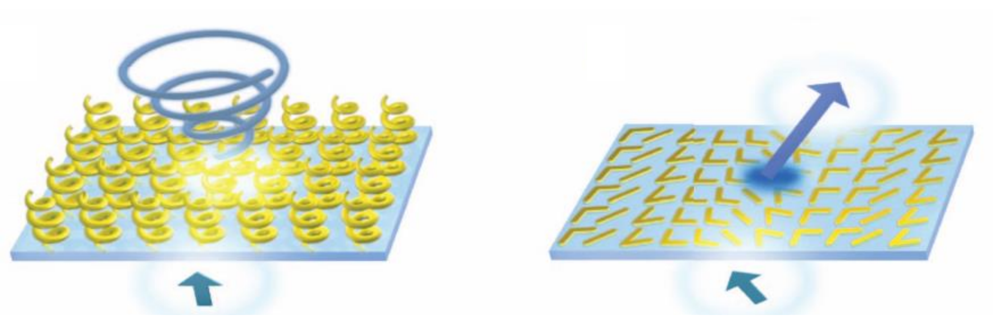


Shelby et al., *Applied Physics Letters* **78** (4): 489 (2001)

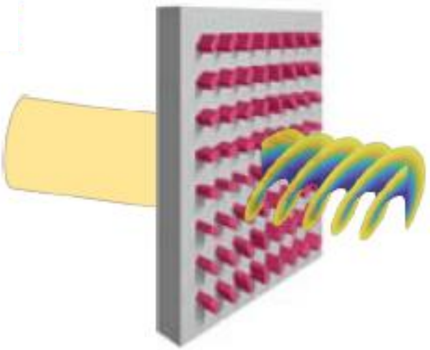
- Artificial materials made by **"meta-atoms" << λ**
- Electromagnetic Radiation sees only an **"average" response**
- Materials with **optical responses not available in nature**

Photonic Metamaterials

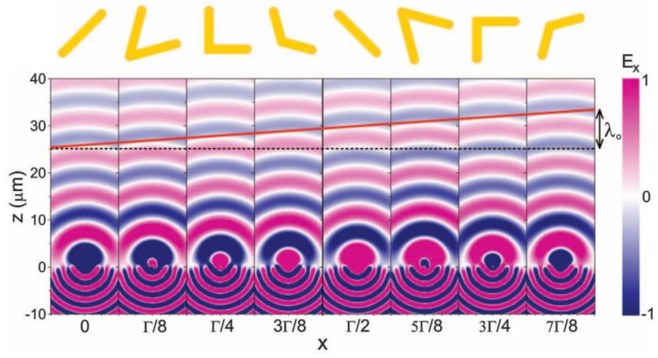
Optical Metamaterials and Metasurfaces



A.F. Koenderink, A. Alù, and A.Polman, *Science* (2015)



K. Wang et al., Phys. Today (2022).

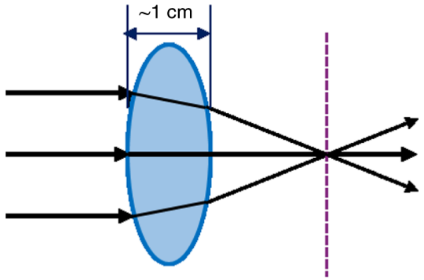


N. Yu et al., Science (2011).

Advanced Optical Functionalities in very **Compact Footprints**

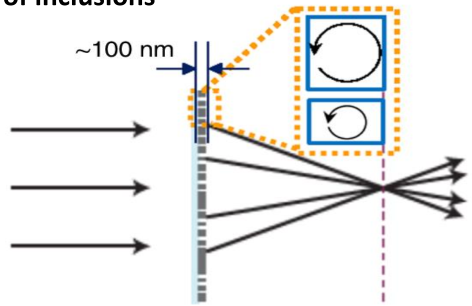
Conventional Lens

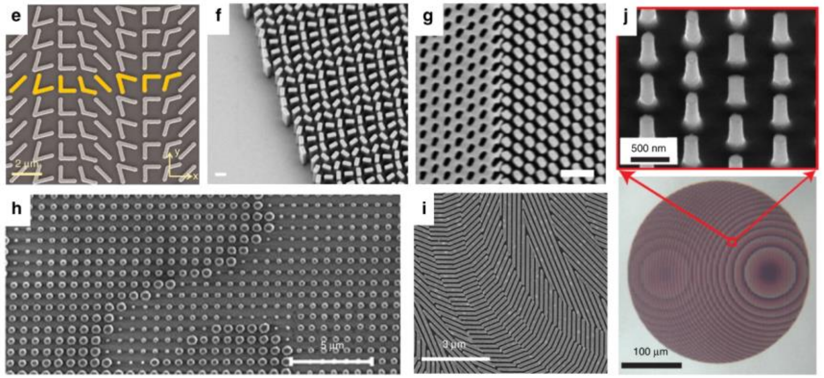
- Phase delay from **thickness and shape**
- Response mainly dictated by **intrinsic material properties**



Metalens

- Phase delay by **scattering from sub-wavelength inclusions**
- Response dictated by **shape, orientation and arrangement of inclusions**





Dragomir and Aharonovich, "Optical metasurfaces: new generation building blocks for multi-functional optics." *Light: Science & Applications* (2018)

Image Processing

Digital Image Processing

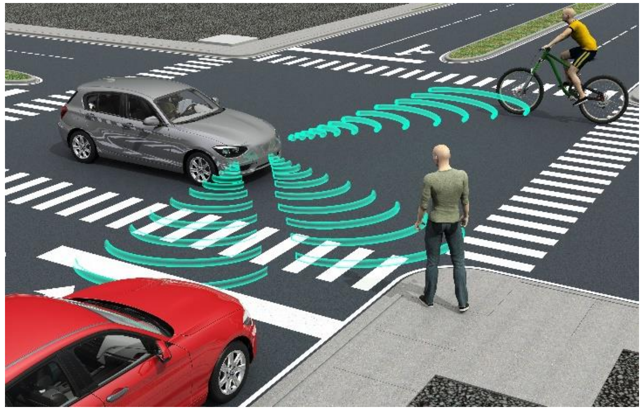
$f(x,y)$

$\nabla^2 \cdot$

$\nabla^2 f(x,y)$

Self-driving cars

Enhance edges to simplify object detection



https://www.rdworldonline.com/

https://towardsdatascience.com/

Digital Image Processing

$f(x,y)$

$\nabla^2 \cdot$

$\nabla^2 f(x,y)$

- Medical Imaging
- Fingerprint Recognition
- Satellite Images
- Robotic Vision
- …

Digital Image Processing

$f(x,y)$

$\nabla^2 \cdot$

$\nabla^2 f(x,y)$

Pros:

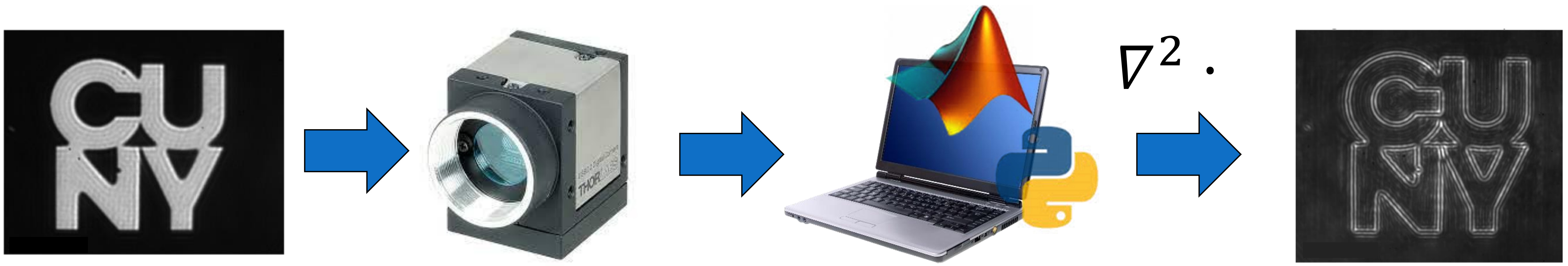
- Programmable
- Highly versatile.

Cons:

- Require hardware for computation.
- Might be “too slow” for certain applications.
- Energy consumption.

Image Processing

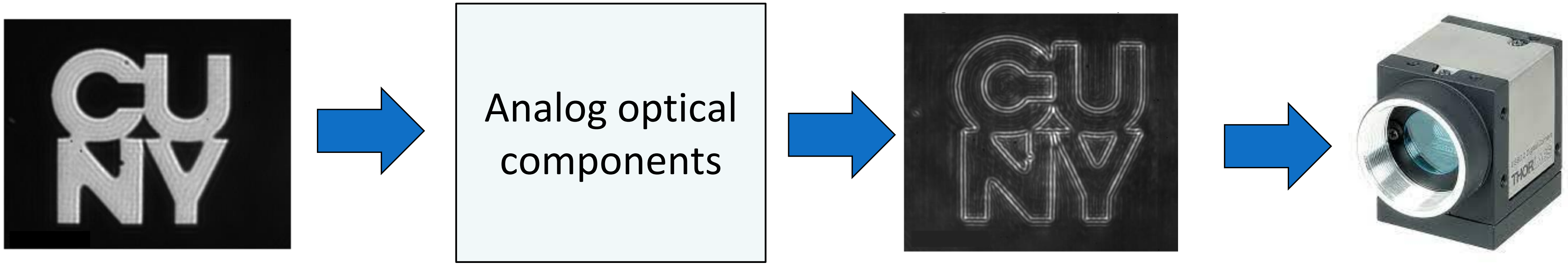
Digital Image Processing



$f(x,y)$

$\nabla^2 f(x,y)$

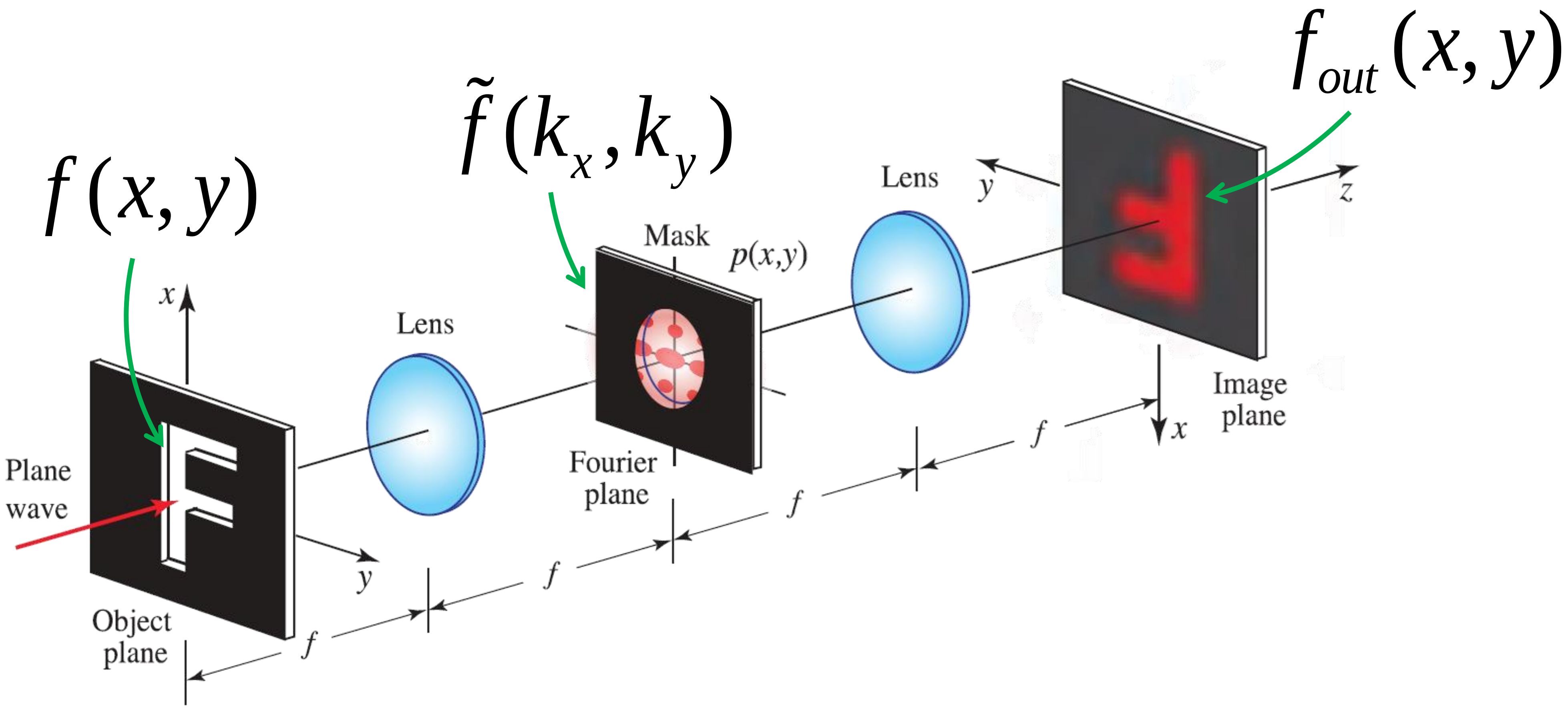
Analog Image Processing



$\boldsymbol{E}_{\mathrm{in}}(x,y,t) = f(x,y)e^{i\omega_0 t}\hat{\boldsymbol{e}}$

$\boldsymbol{E}_{\mathrm{out}}(x,y,t) = \nabla^2 f(x,y)e^{i\omega_0 t}\hat{\boldsymbol{e}}$

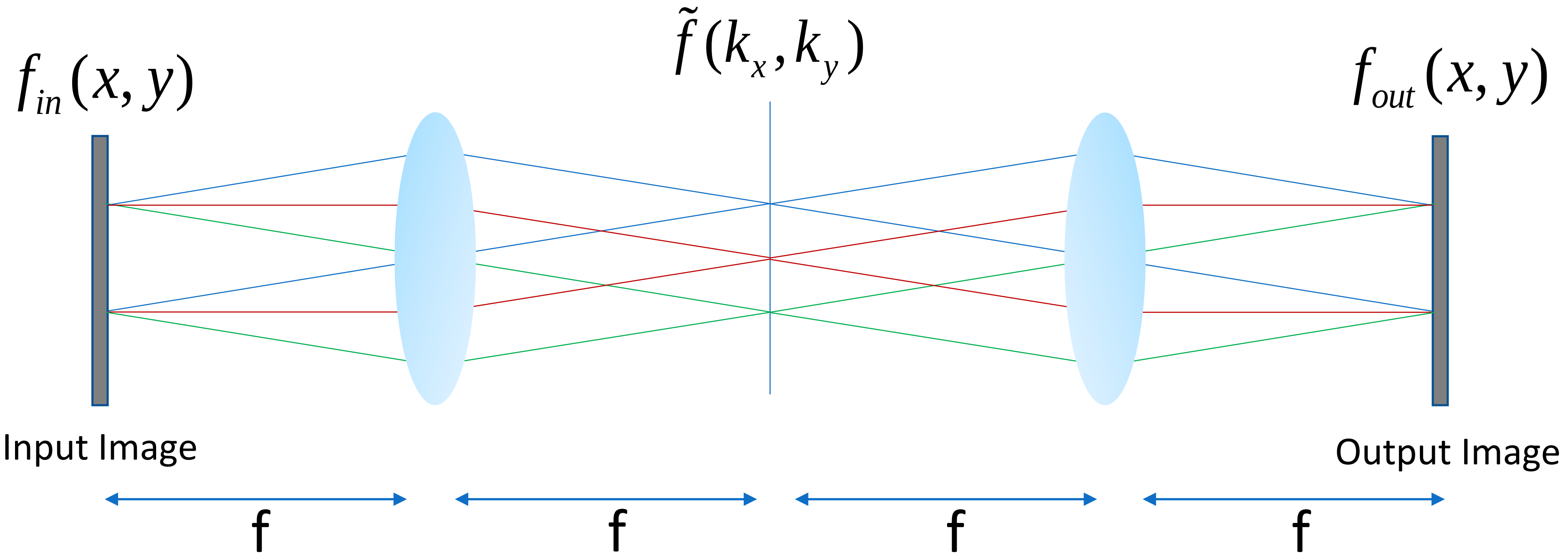
Standard Method for K-Space Filtering



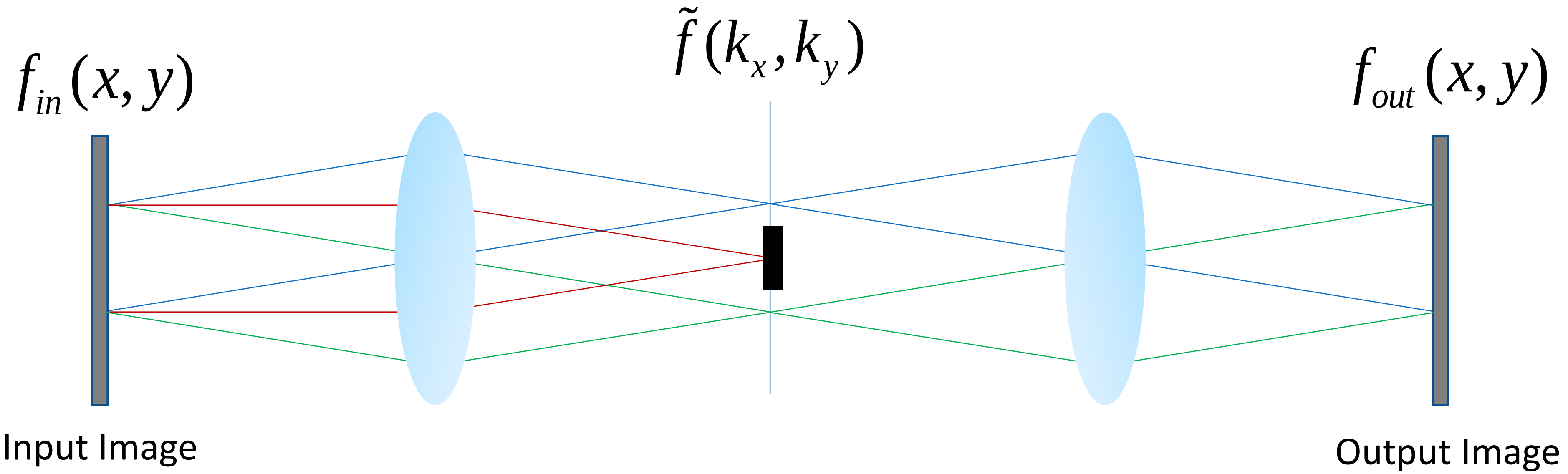
Adapted from “Fundamentals of Photonics”, Saleh & Teich, Wiley

Analog Image Processing: Fourier Optics

K-space filtering with a 4F system

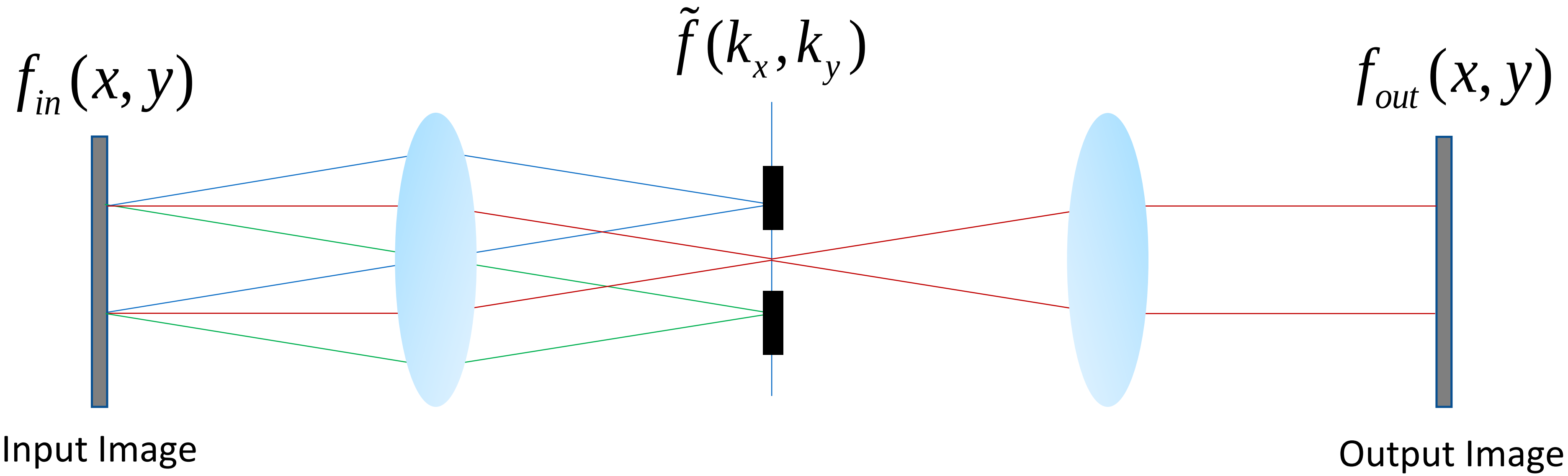


K-space filtering with a 4F system



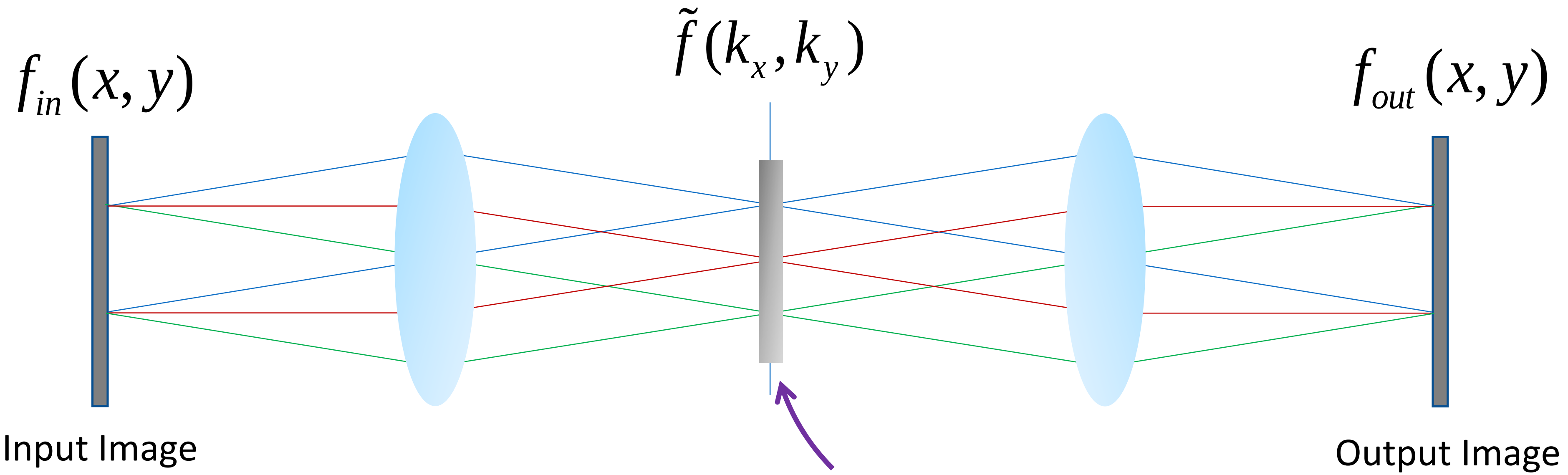
High-Pass filter

K-space filtering with a 4F system



Low-Pass filter

K-space filtering with a 4F system



Mask with arbitrary spatially dependent profile

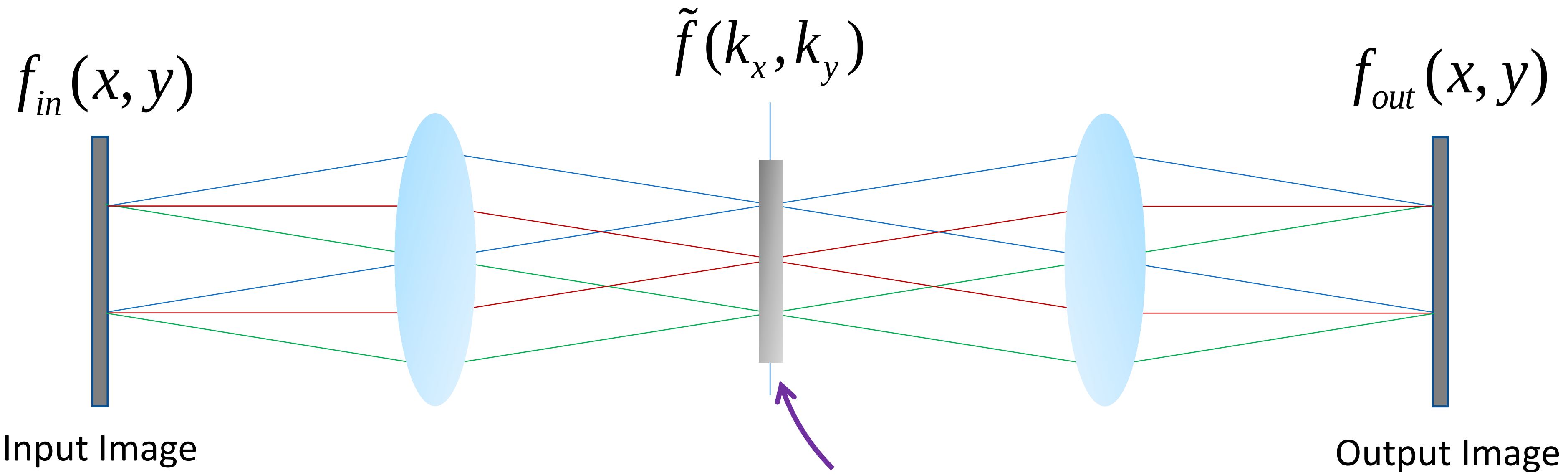
$$t(x, y) \rightarrow t(k_x, k_y)$$

Transfer Function

$$f_{out}(x, y) = \iint dxdy\, t(k_x, k_y)\, \tilde{f}(k_x, k_y) e^{-i(k_x x + k_y y)}$$

Analog Image Processing: Fourier Optics

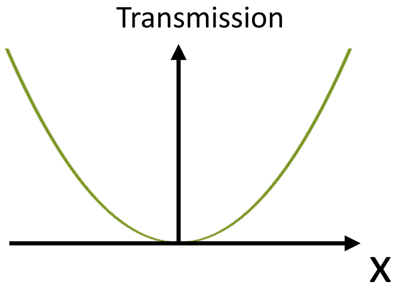
K-space filtering with a 4F system



Mask with arbitrary spatially dependent profile

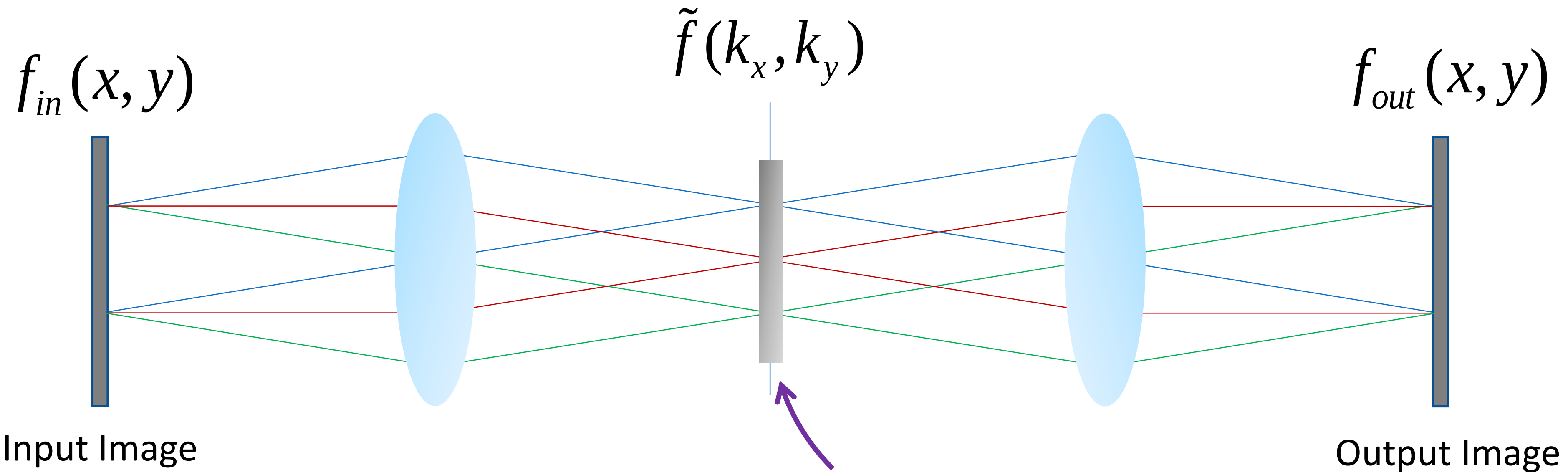
$$t(x, y) \rightarrow t(k_x, k_y)$$

Example:
Laplacian operation



$$t(k_x, k_y) \propto (k_x^2 + k_y^2) \Rightarrow f_{out}(x, y) \propto (\partial_x^2 + \partial_y^2) f(x, y)$$

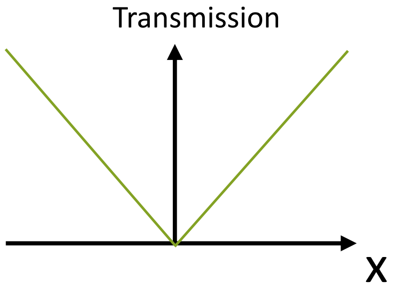
K-space filtering with a 4F system



Mask with arbitrary spatially dependent profile

$$t(x, y) \rightarrow t(k_x, k_y)$$

Example:
Phase Contrast

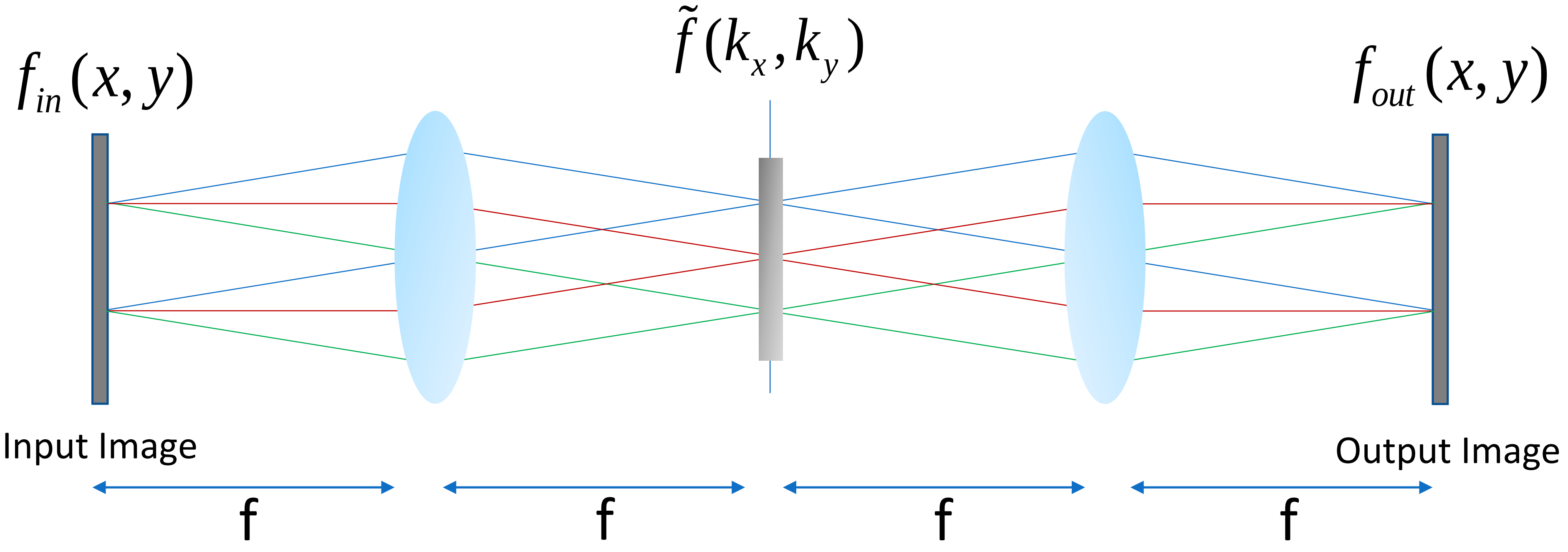


$$t(k_x, k_y) \propto k_x$$

$$f_{in}(x, y) = f_0 e^{i\phi(x,y)}$$

$$\Rightarrow \quad f_{out}(x, y) \propto \partial_x \phi(x, y)$$

Analog Image Processing: Fourier Optics



$$f_{out}(x,y) = \iint dxdy\, t(k_x,k_y)\, \tilde{f}(k_x,k_y) e^{-i(k_x x + k_y y)}$$

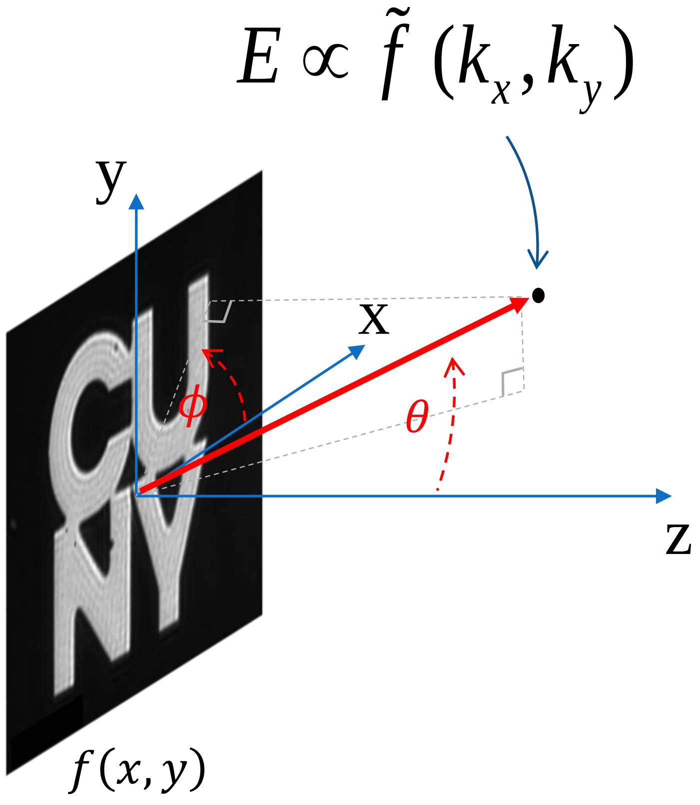
Pros: very easy to target a desired k-vector

Cons: inherently **bulky technique**:

- Need to access the Fourier space
- Total footprint ≥ 4f
- Not suited for integrated applications (smartphones, compact microscopes, etc.)

We do not need to physically access the back focal plane to obtain the Fourier transform

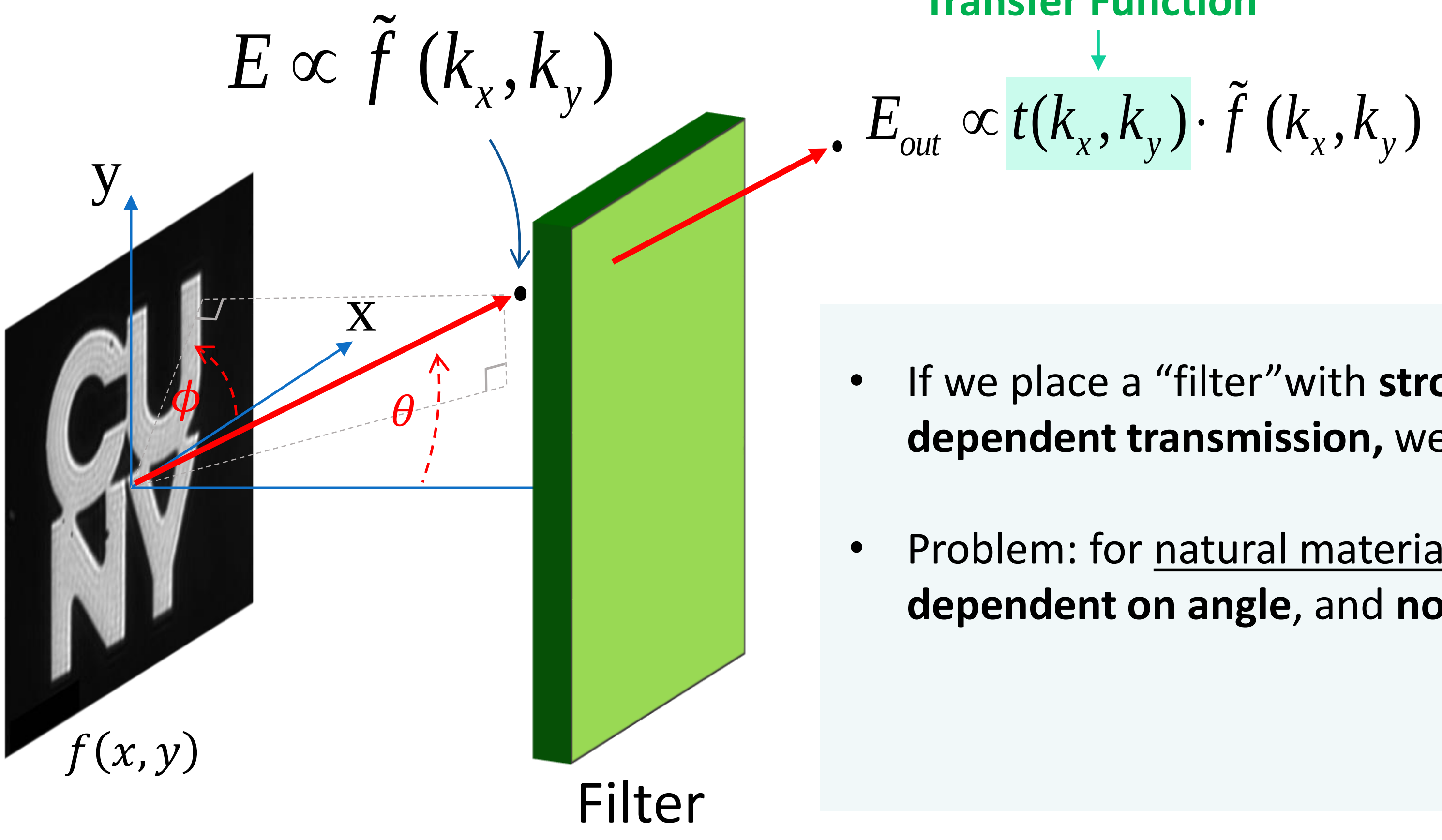
Optics **gives us the Fourier transform for free (i.e., without lenses)**

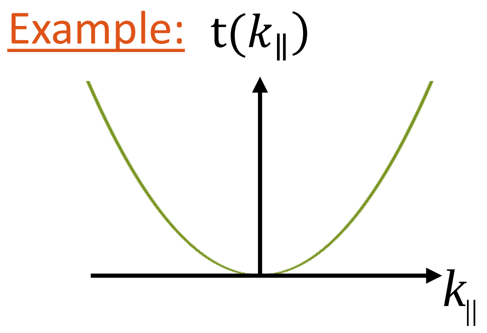


Each diffracted wave, propagating at a specific angle, **"carries" a different Fourier component**

Analog Signal Processing with Metasurfaces

We do not need to physically access the back focal plane to obtain the Fourier transform





- If we place a "filter" with **strong and tailored angle-dependent transmission,** we could do k-space filtering
- Problem: for natural materials, transmission **is weakly dependent on angle**, and **not tunable**

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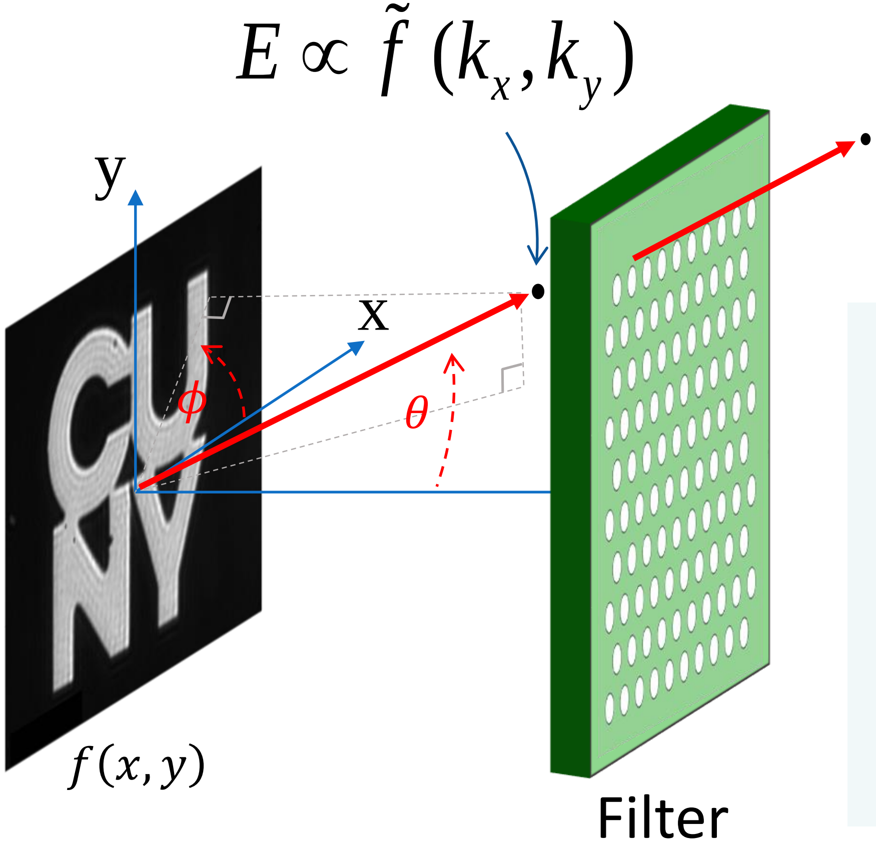
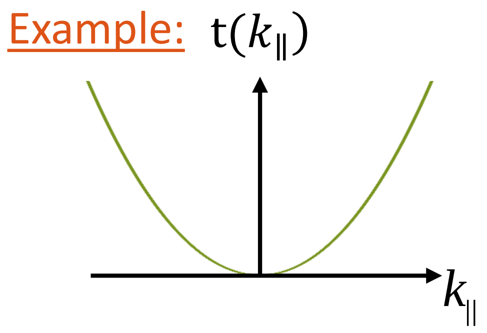


Transfer Function

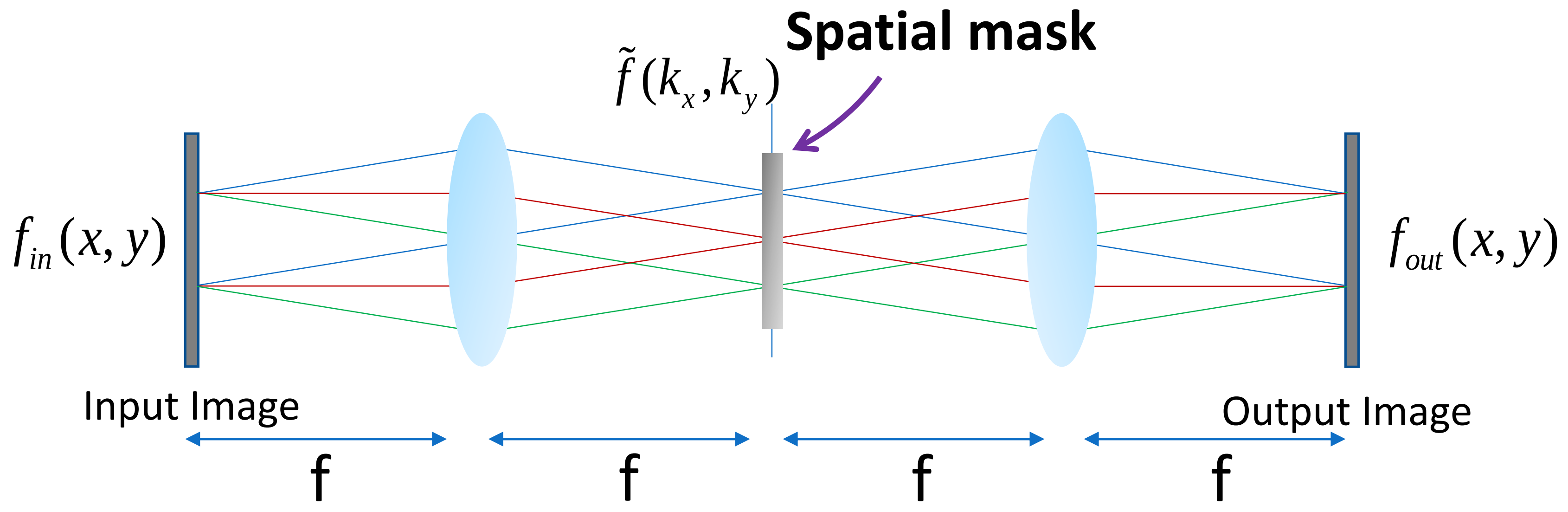
$$E_{out} \propto t(k_x, k_y) \cdot \tilde{f}\,(k_x, k_y)$$



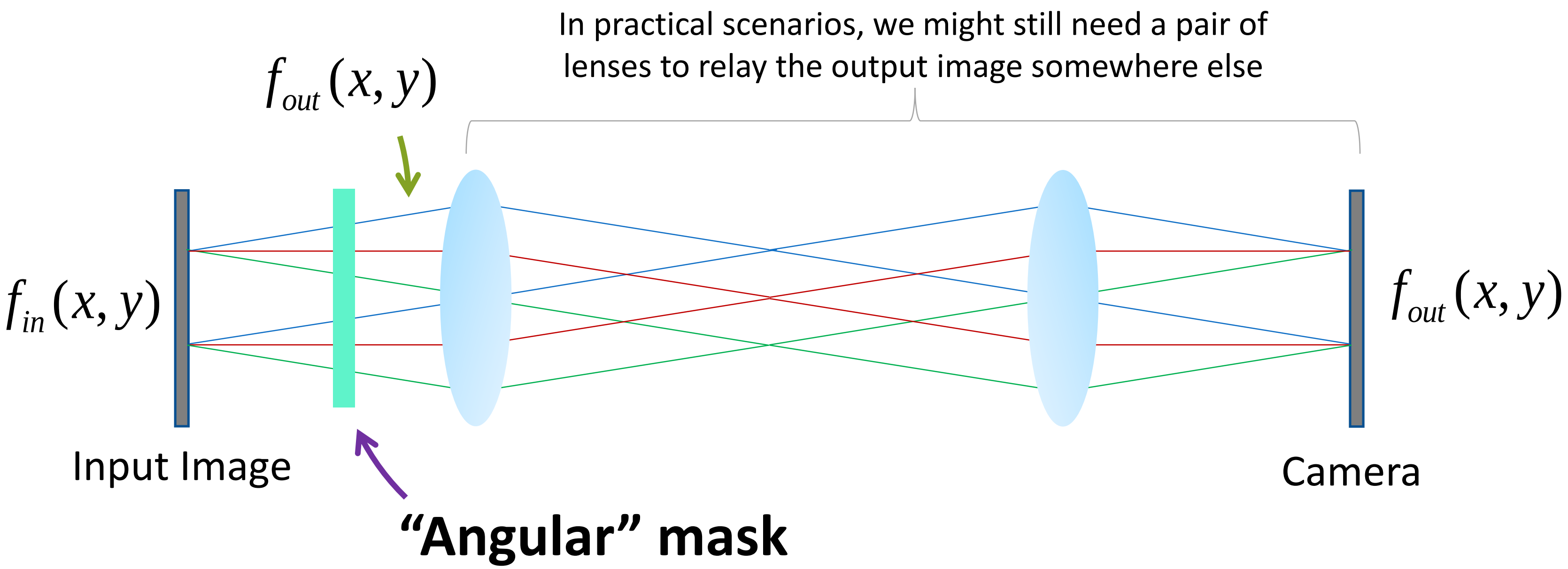
- If we place a "filter"with **strong and tailored angle-dependent transmission,** we could do k-space filtering
- Problem: for natural materials, transmission **is weakly dependent on angle**, and **not tunable**
- **But it can be done with a metasurface!**

4F or Not 4F – This is the Question

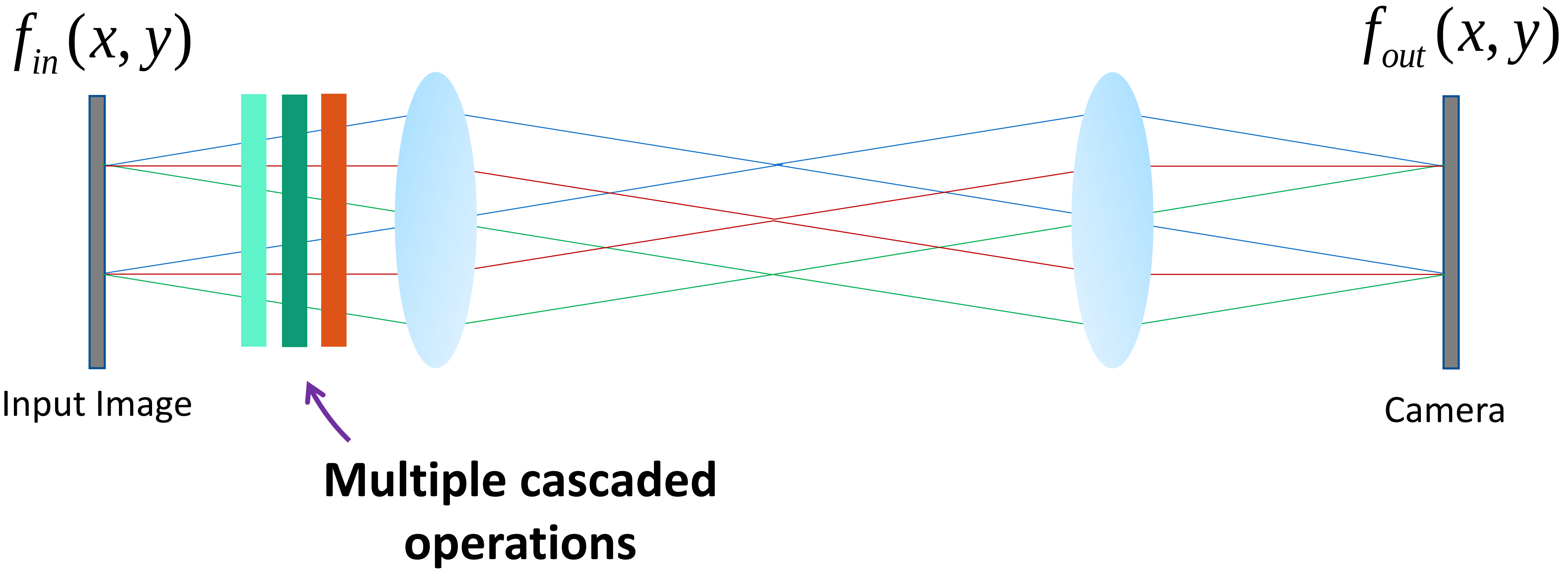
Standard 4F
k-space filtering



The "metasurface" approach



Scalability of the 4F-Less Approach



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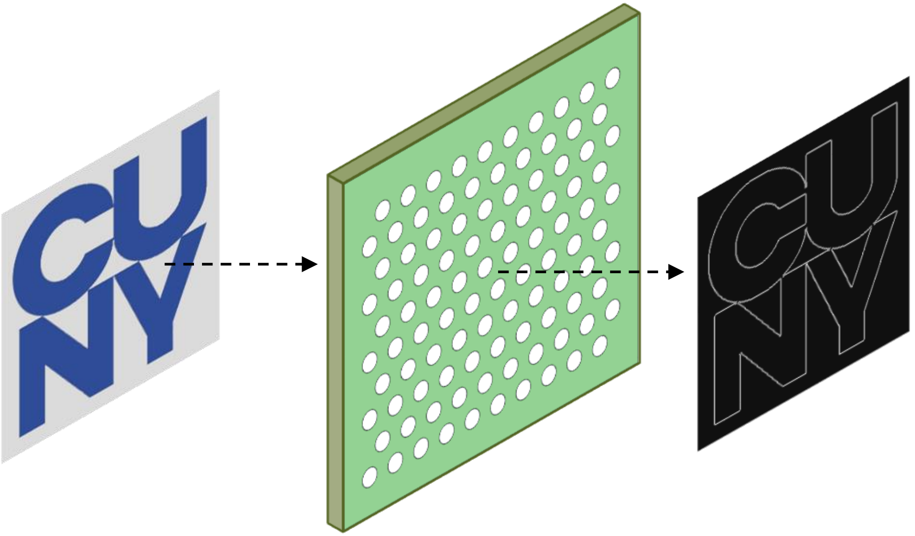
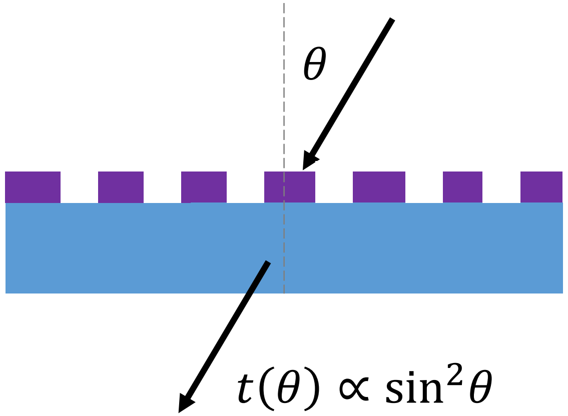
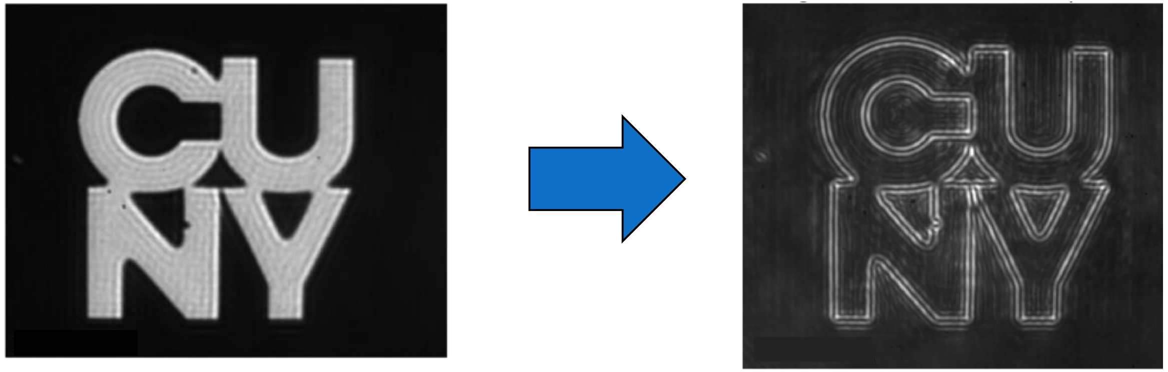
Standard Approach to obtain a "Laplacian Response"





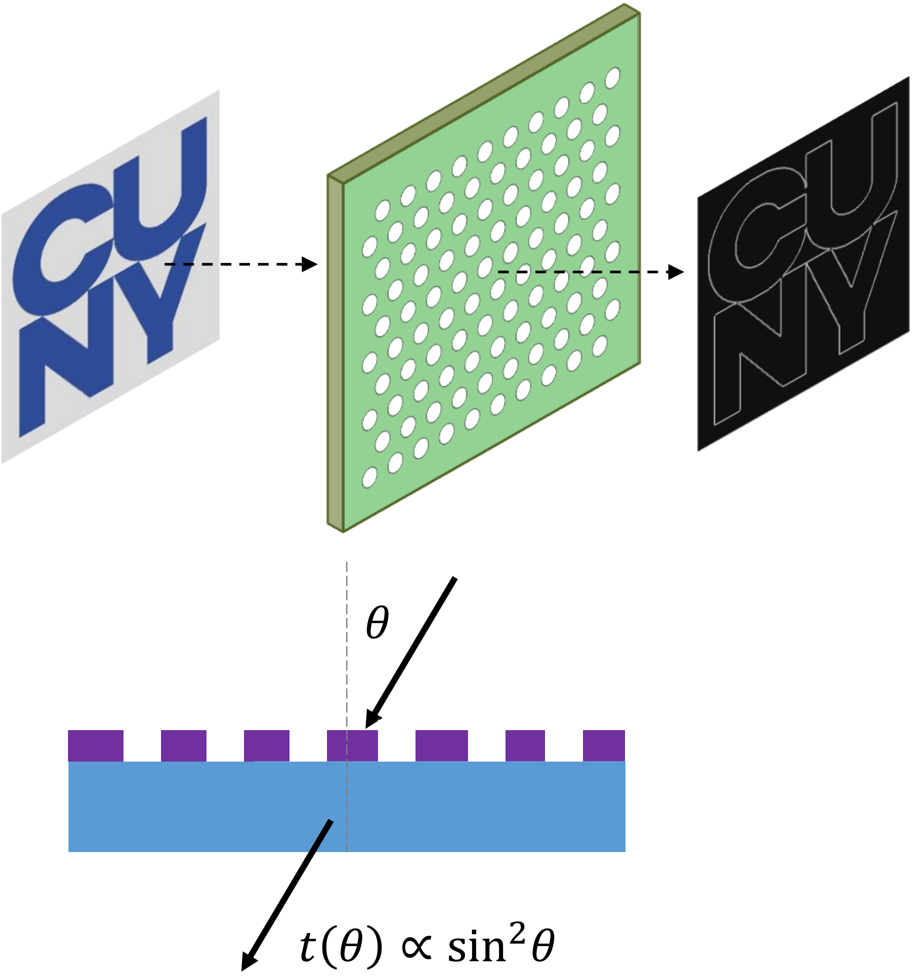
$f_{in}(x,y)$ $\nabla^2 f_{in}(x,y)$

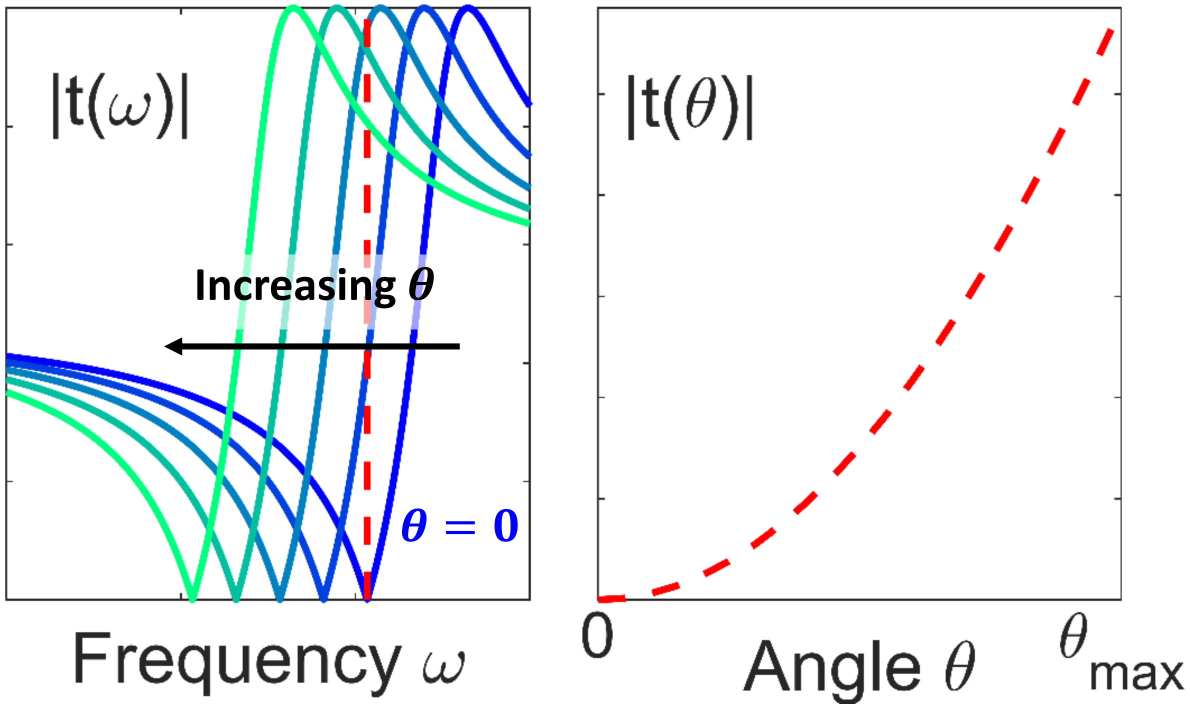


$$f_{out}(x,y) = (\partial_x^2 + \partial_y^2)\, f_{in}(x,y)$$

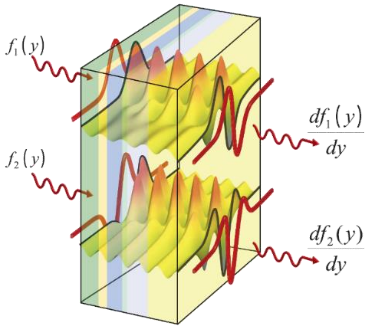
$$f_{out}(k_x,k_y) = -(k_x^2 + k_y^2)\, f_{in}(k_x,k_y)$$

Standard Approach to obtain a "Laplacian Response"

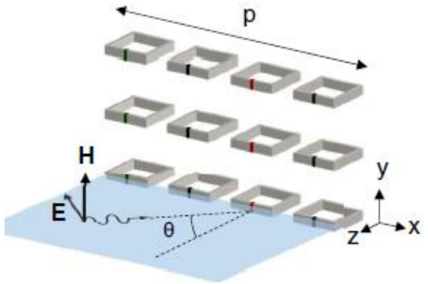




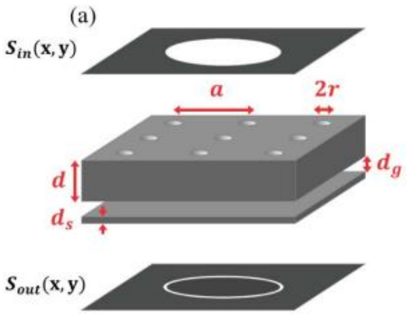
Analog Image Processing with Metasurfaces



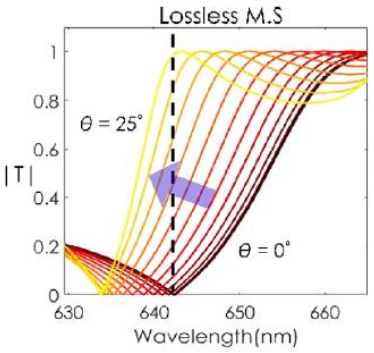
Silva, et al., **Science** 343(6167), 160-163 (2014)



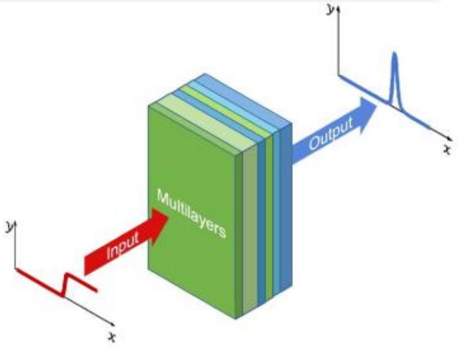
Kwon et al., **Phys. Rev. Lett.** 121(17), 173004 (2018)



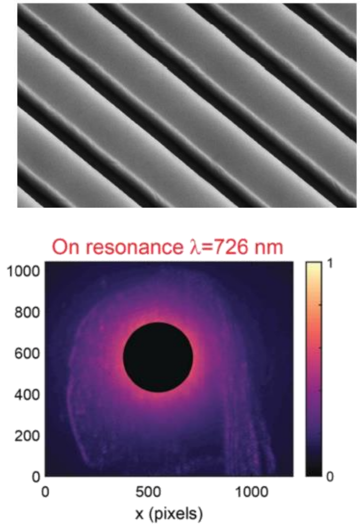
Guo et al., **Optica** 5(3), 251-256 (2018)



Kwon et al., **ACS Photonics** 7(7), 1799-1805 (2020)

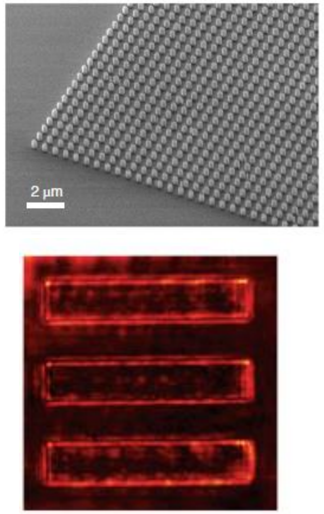


Xue et al., **J. of Optics** 23(12), 125004 (2021)



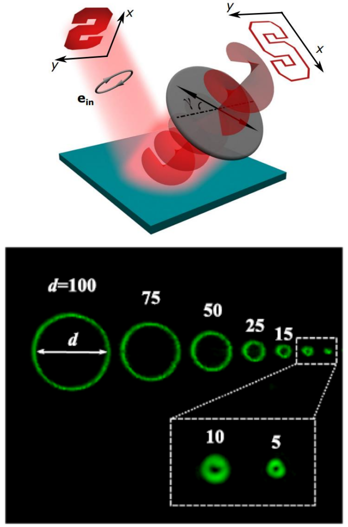
Cordaro et al., **Nano Letters** 19(12), 8418-8423(2019)

Polman's & Alu's group



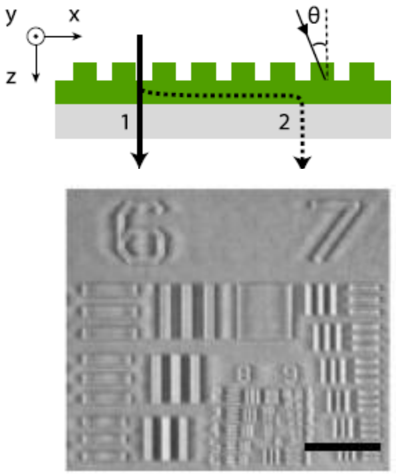
Zhou et al., **Nature Photonics** 14(5), 316-323(2020)

Valentine's group



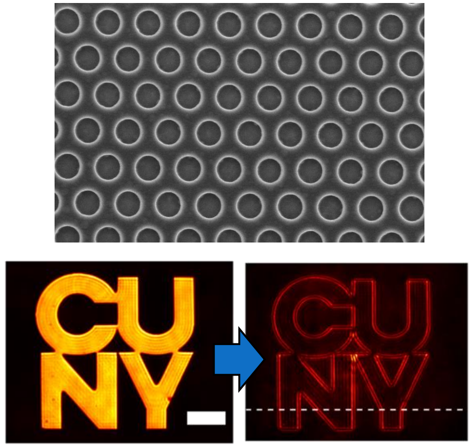
Zhu et al., **Nat. Comm.** 12:680 (2021)

Fan's group



Ji et al., **Nat. Comm.** 13.1, 7848 (2022)

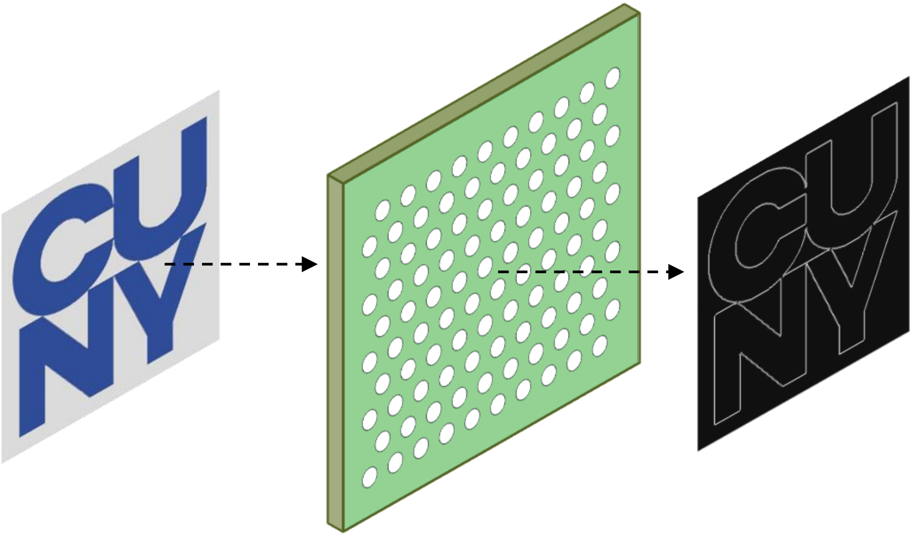
Brongersma's group

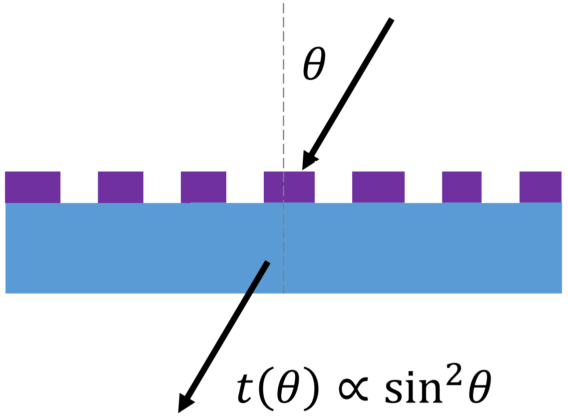


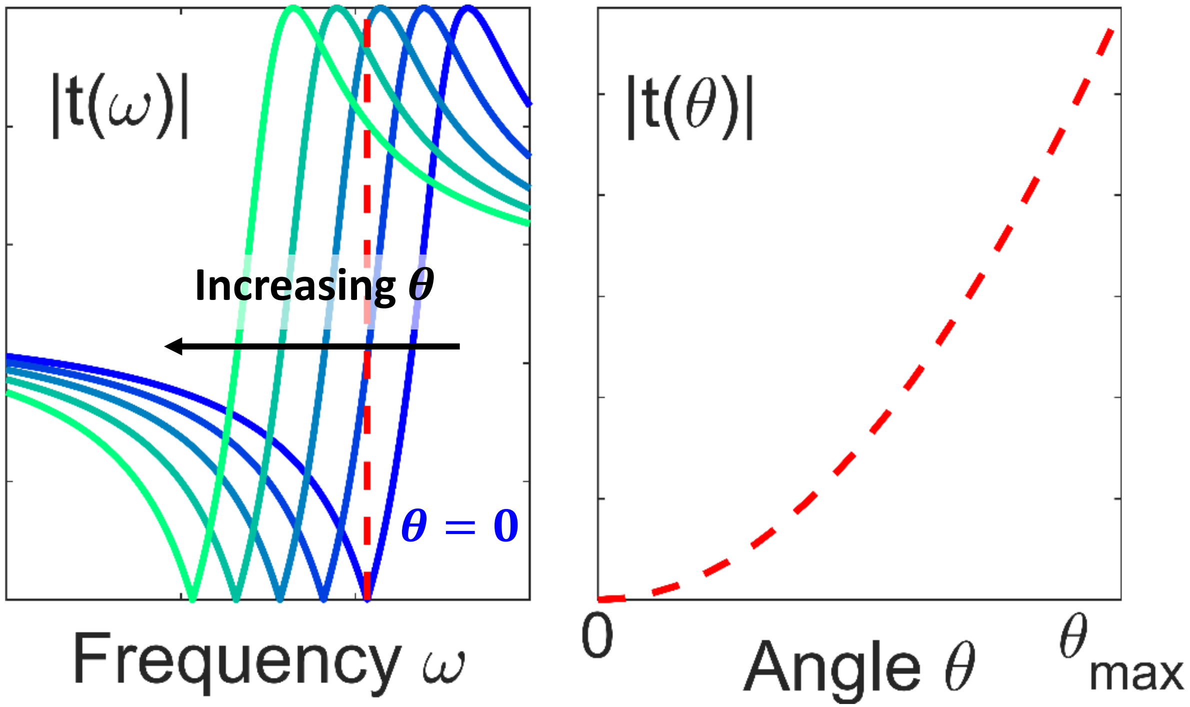
Cotrufo et al., *under review* arXiv : 2212.03468

Alu's group

Standard Approach to obtain a "Laplacian Response"

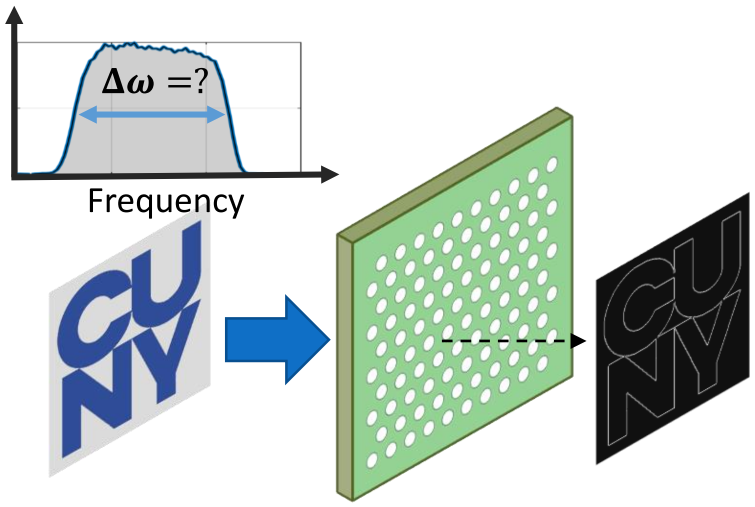




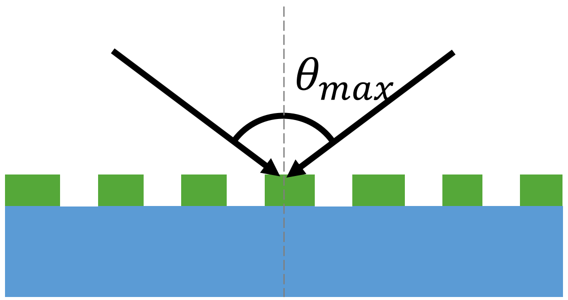


Important Figures of Merit

1. Spectral Bandwidth

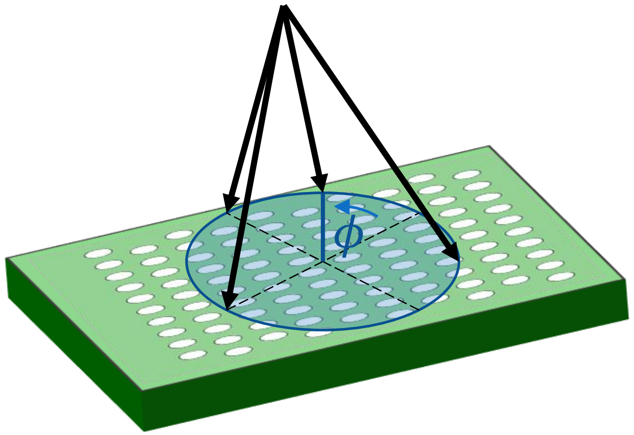


2. Numerical Aperture

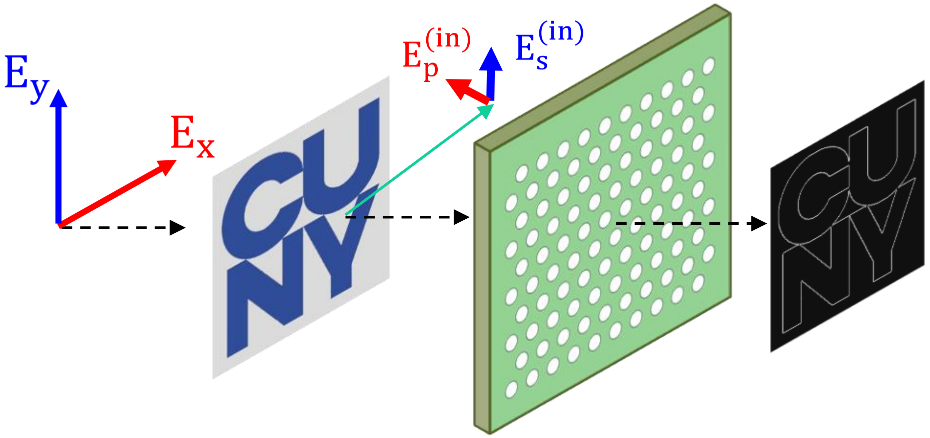


$NA = \sin\theta_{max}$

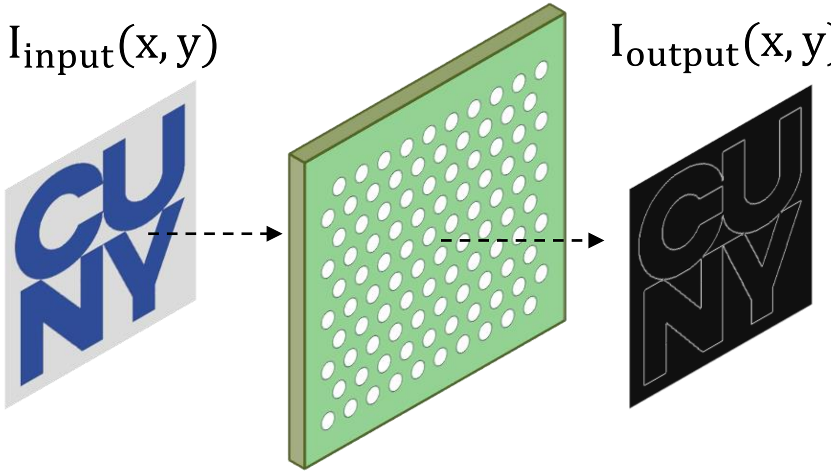
3. Azimuthal Isotropy



4. Polarization (in)dependence

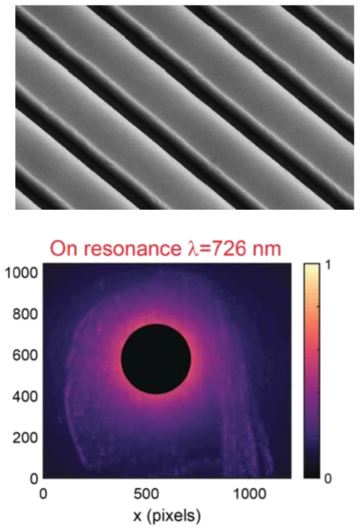


5. Efficiency

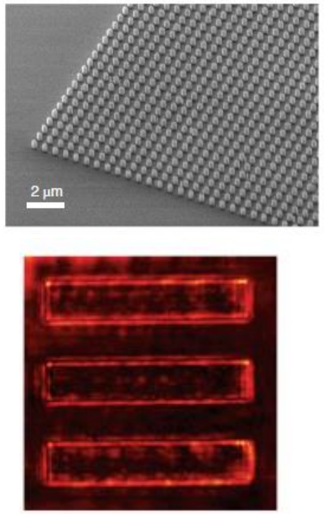


$\frac{I_{output}}{I_{input}} = ?$

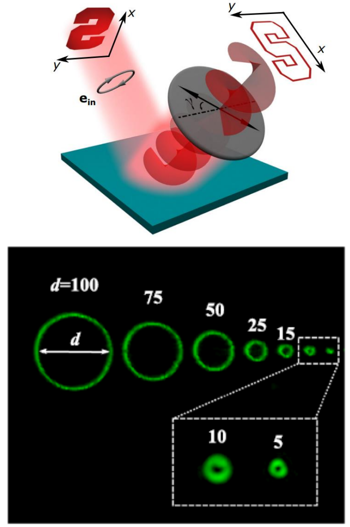
Analog Image Processing with Metasurfaces



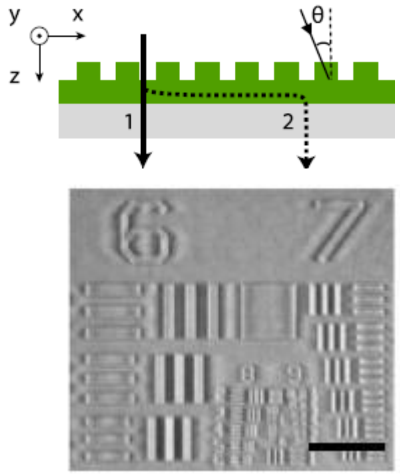
Cordaro et al., **Nano Letters** 19(12), 8418-8423(2019)
Polman's & Alu's group



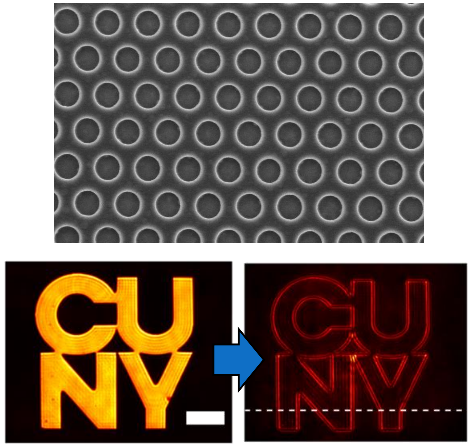
Zhou et al., **Nature Photonics** 14(5), 316-323(2020)
Valentine's group



Zhu et al., **Nat. Comm.** 12:680 (2021)
Fan's group

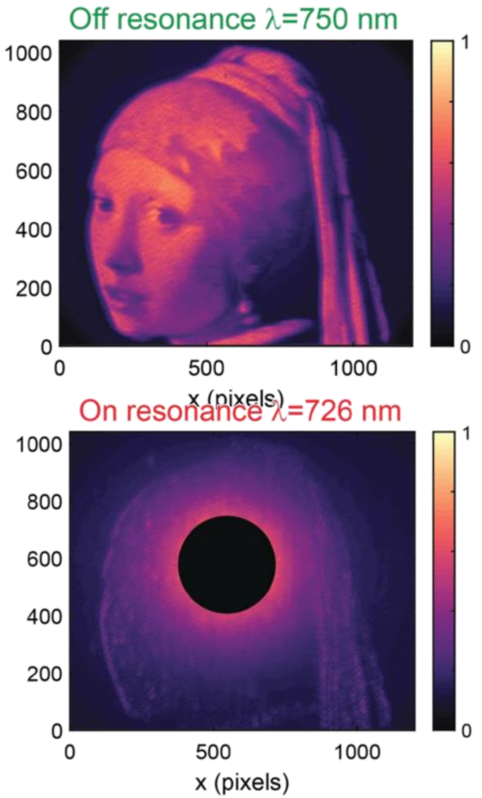


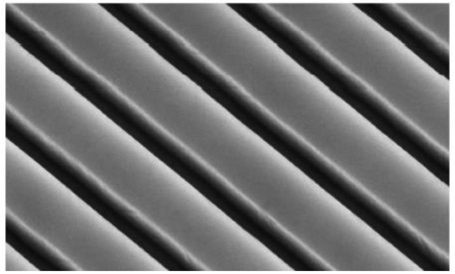
Ji et al., **Nat. Comm.** 13.1, 7848 (2022)
Brongersma's group



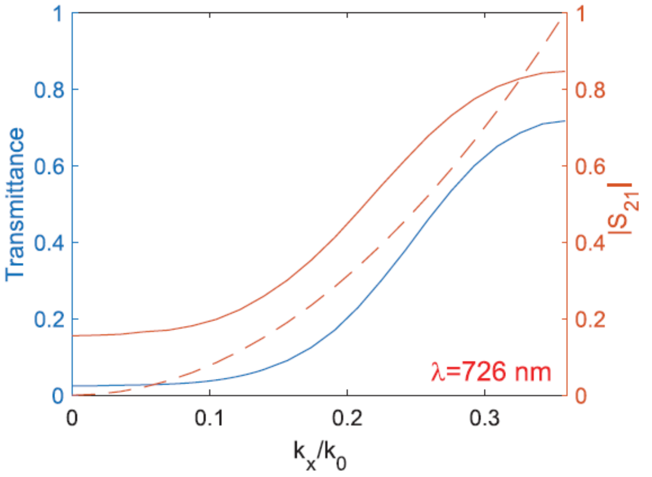
Cotrufo et al., *under review*. arXiv : 2212.03468
Alu's group

Experimental Works on 4F-Less Edge Detection

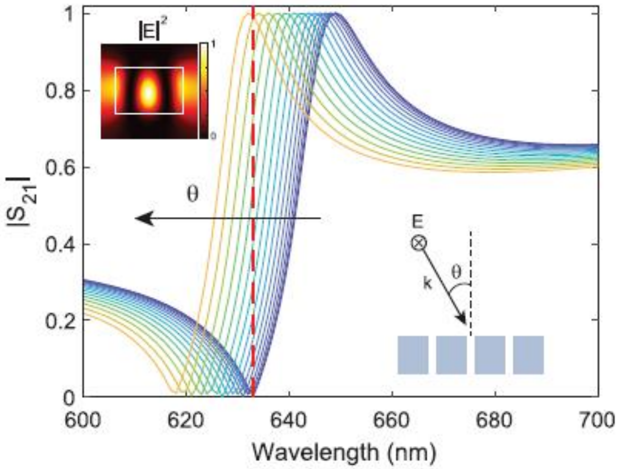




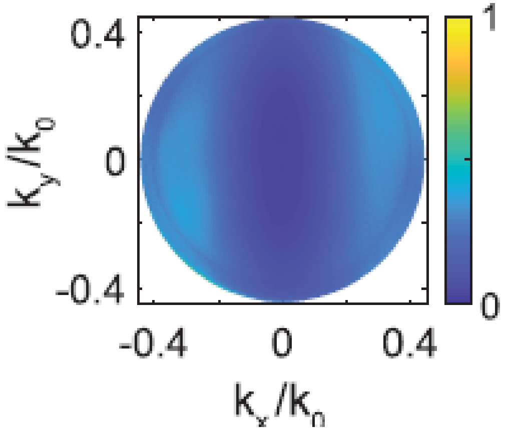
Large NA



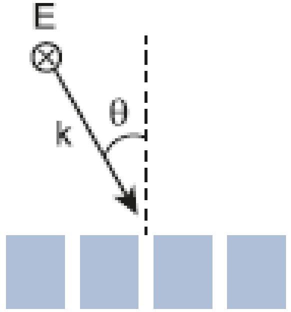
Small Bandwidth



Very anisotropic (C2 symmetry)

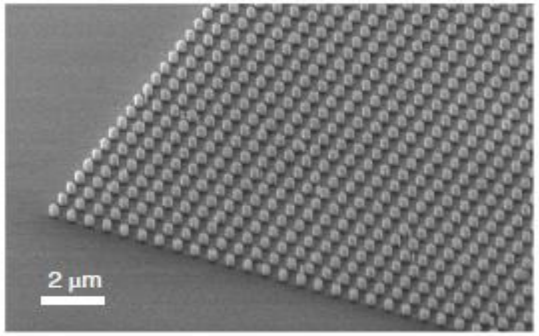


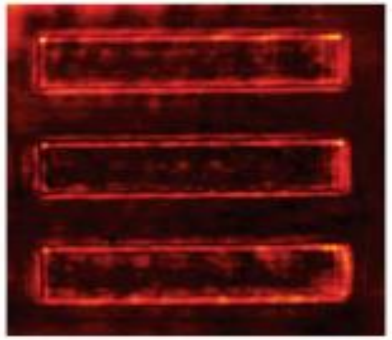
Strongly Polarization-Dependent



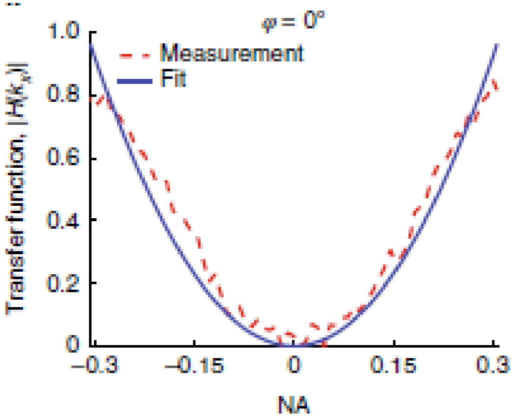
Cordaro et al., **Nano Letters** (2019) **(Andrea Alu's and Albert Polman's groups)**

Experimental Works on 4F-Less Edge Detection

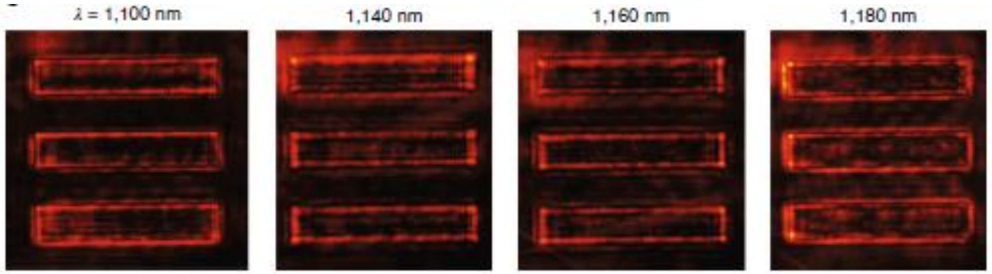




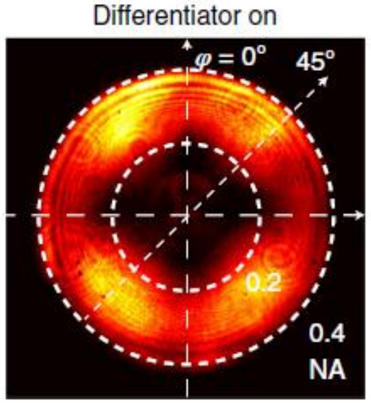
Large NA (0.32)



Large Bandwidth (~80nm)

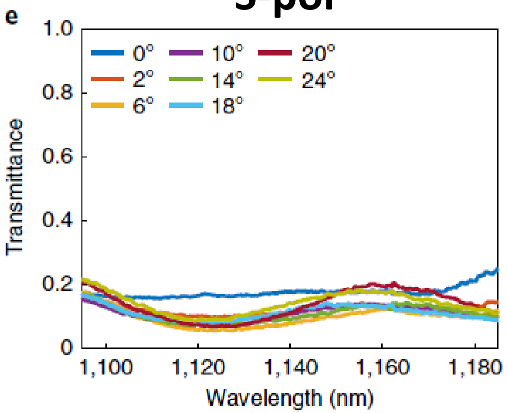


Improved Isotropy (C4 symmetry)

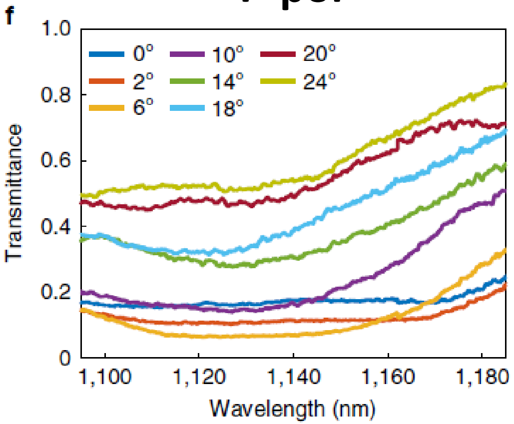


Polarization-Dependent

S-pol

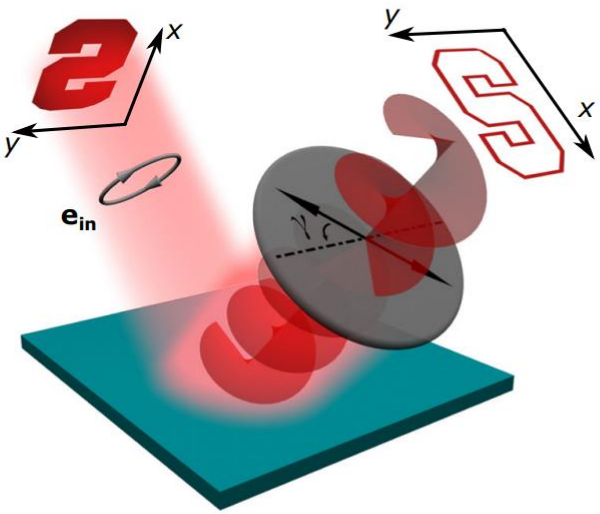


P-pol

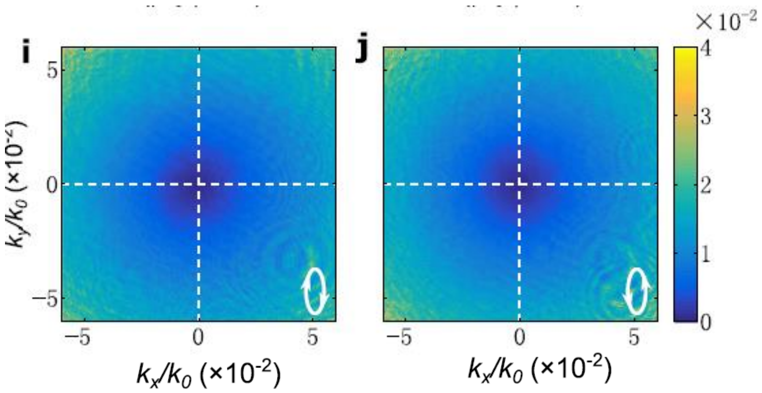


Zhou et al., **Nature Photonics** (2020) (**Jason Valentine's group)**

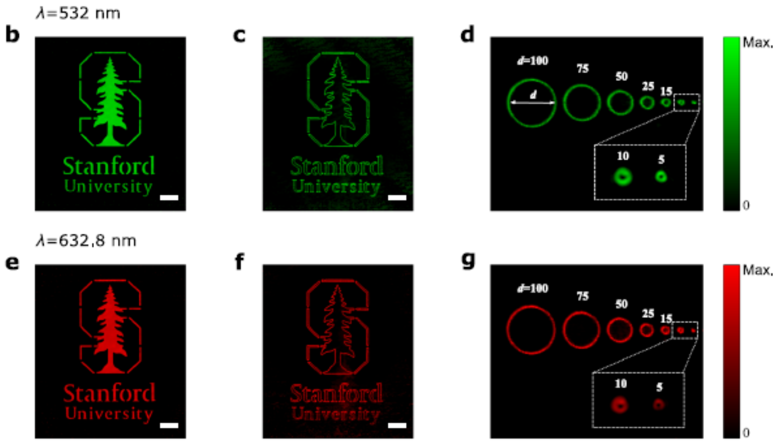
Experimental Works on 4F-Less Edge Detection



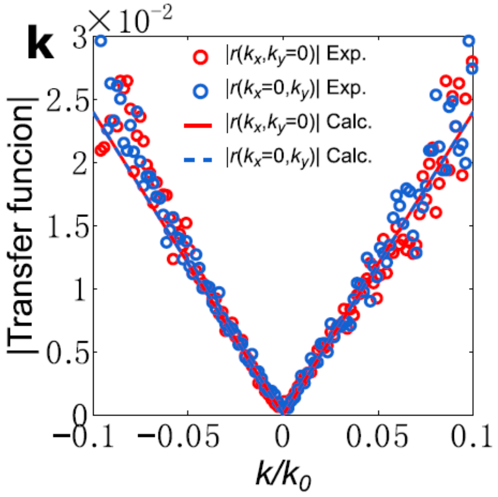
Excellent Isotropy



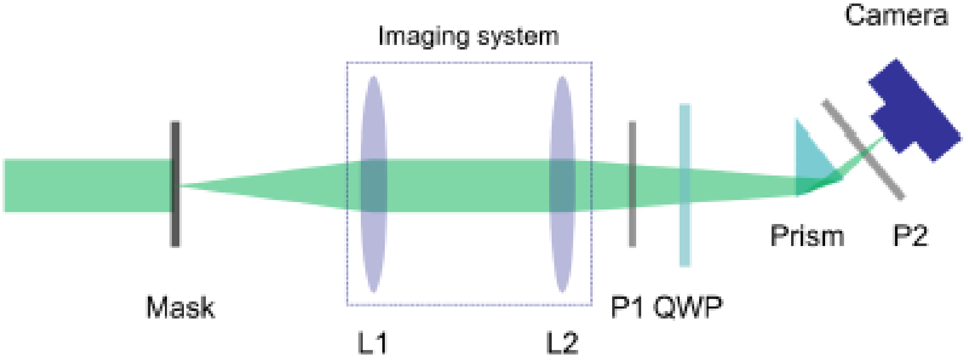
Very Large Bandwidth



Limited NA and Efficiency



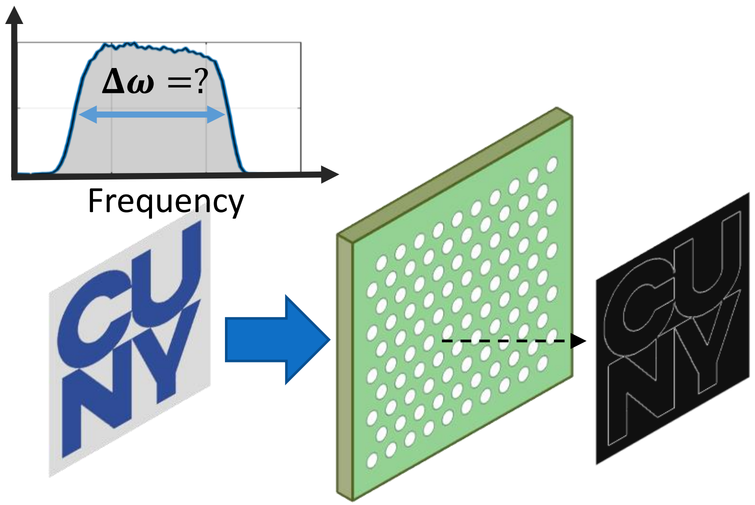
Polarization-Dependent, and need for polarization optics



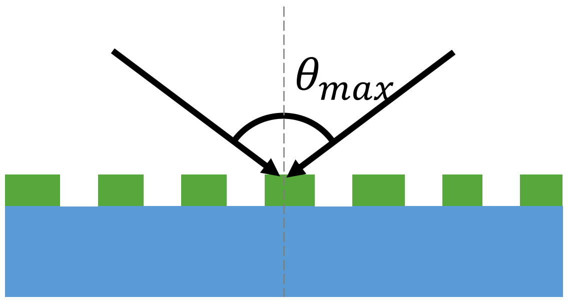
Zhu et al., **Nature Communications** (2021) **(Shanhui Fan's group)**

Important Figures of Merit

1. Spectral Bandwidth

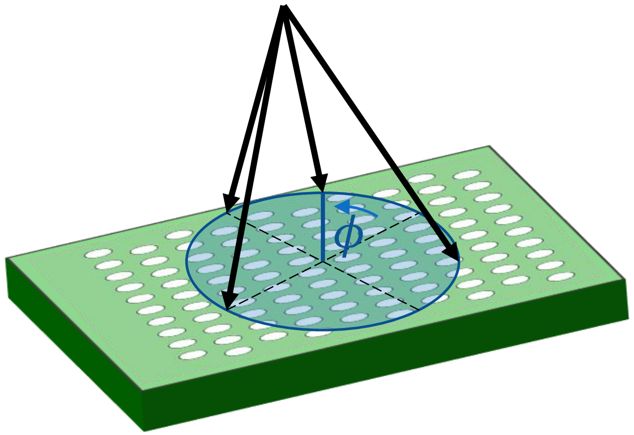


2. Numerical Aperture

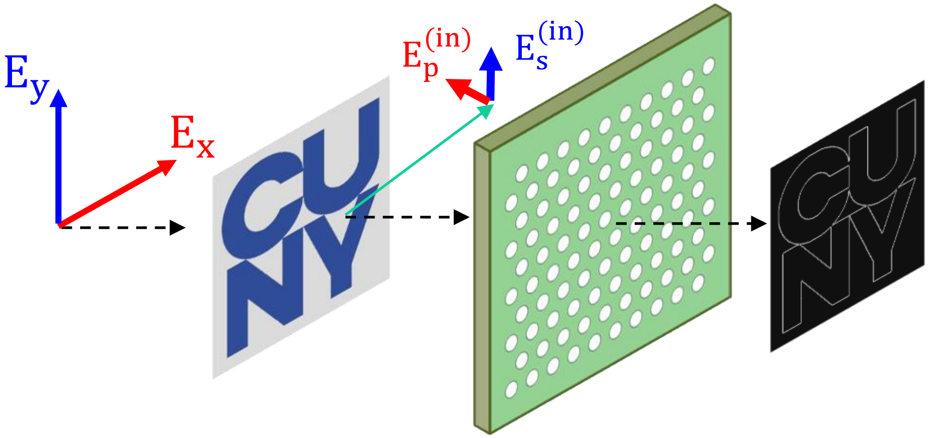


$$NA = \sin\theta_{max}$$

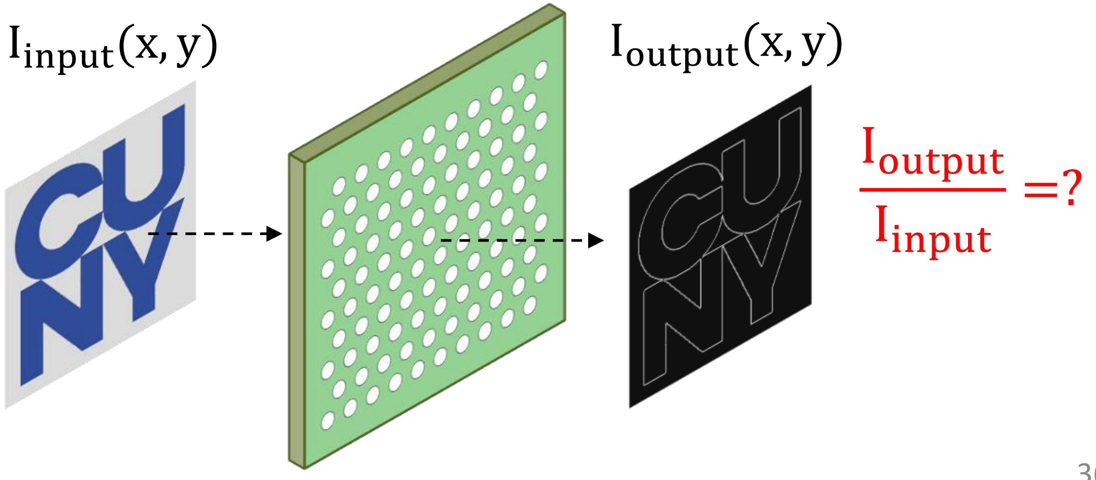
3. Azimuthal Isotropy



4. Polarization (in)dependence



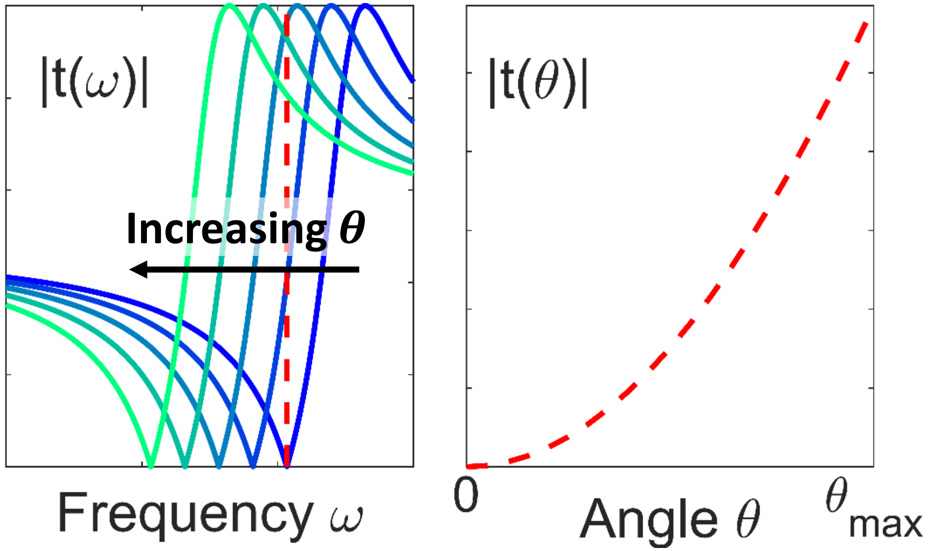
5. Efficiency



Broadband, High-Efficiency and High-NA Edge Detection

Ideal transfer function: $t(\theta, \phi) \propto \sin^2 \theta$

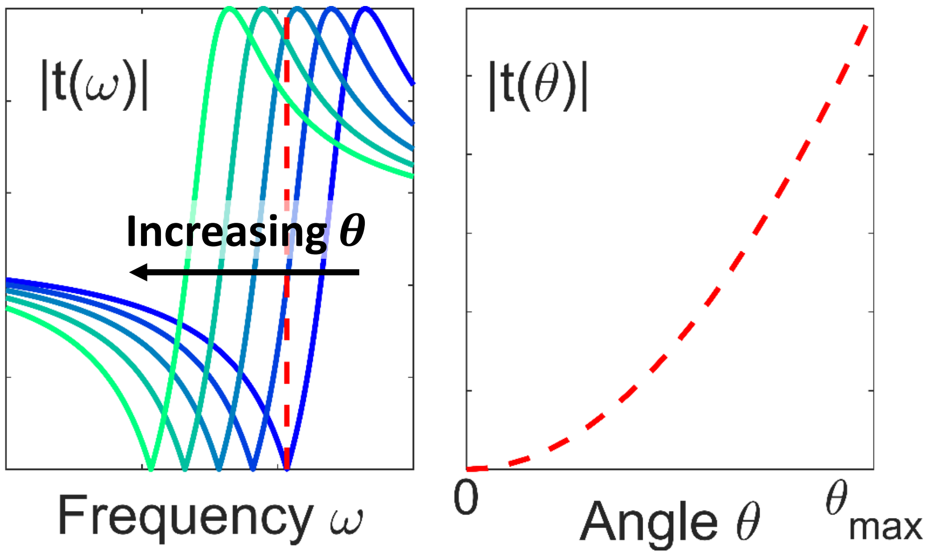
Standard Approach



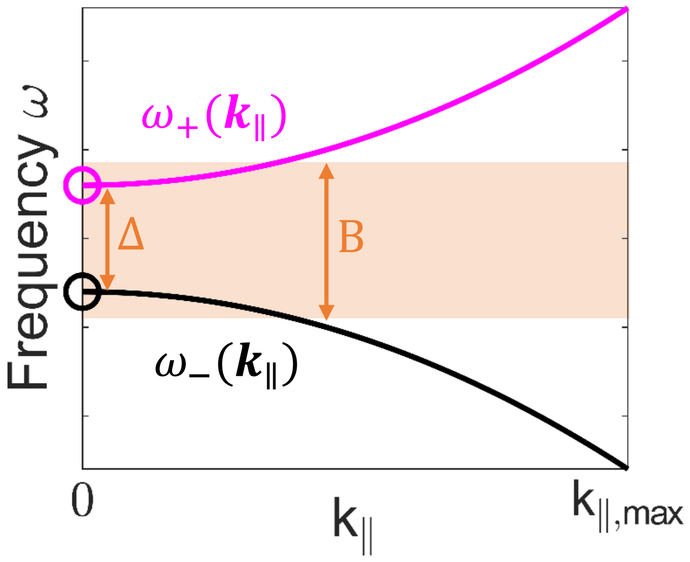
Broadband, High-Efficiency and High-NA Edge Detection

Ideal transfer function: $t(\theta, \phi) \propto \sin^2 \theta$

Standard Approach



Our Approach: <u>Dispersion Engineering</u>

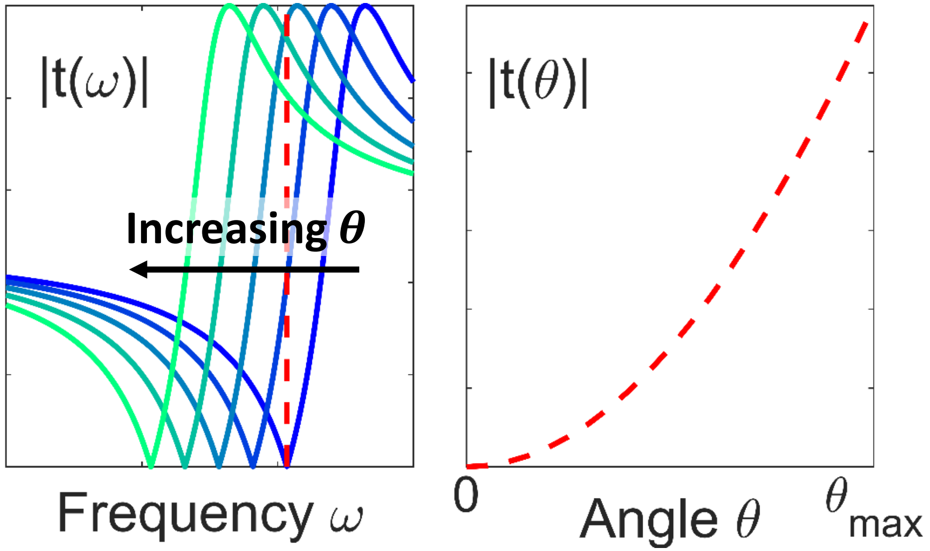


MC*, A. Arora*, S. Singh, A. Alù, *under review* (2023), **arXiv.2212.03468**

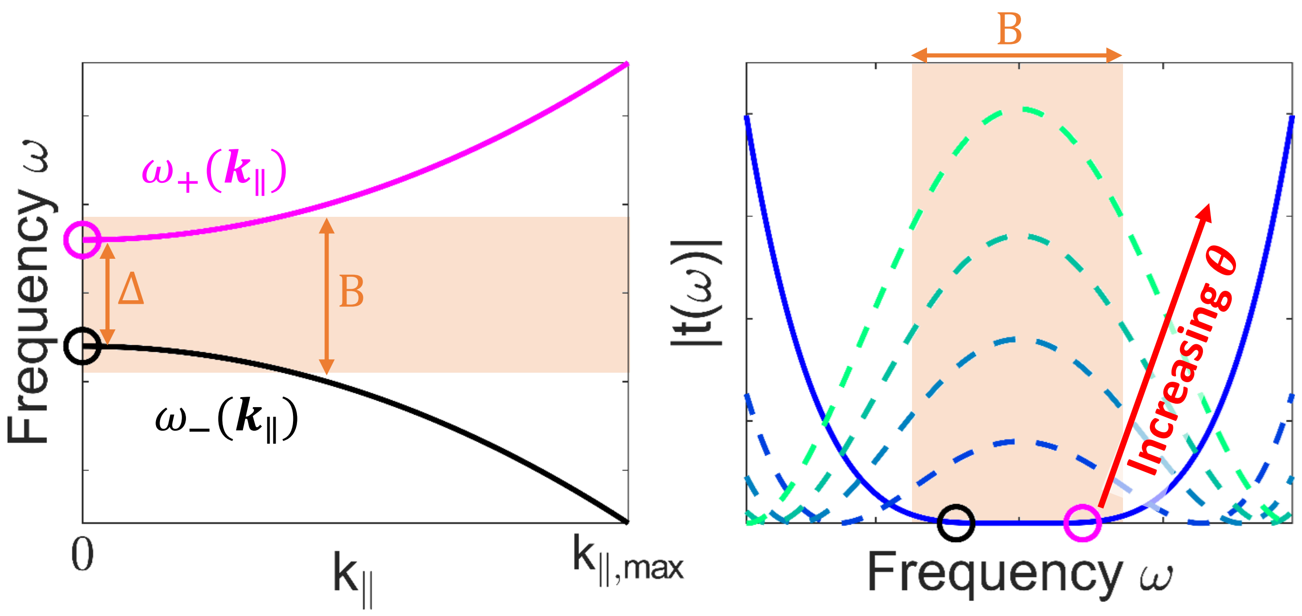
Broadband, High-Efficiency and High-NA Edge Detection

Ideal transfer function: $t(\theta, \phi) \propto \sin^2 \theta$

Standard Approach



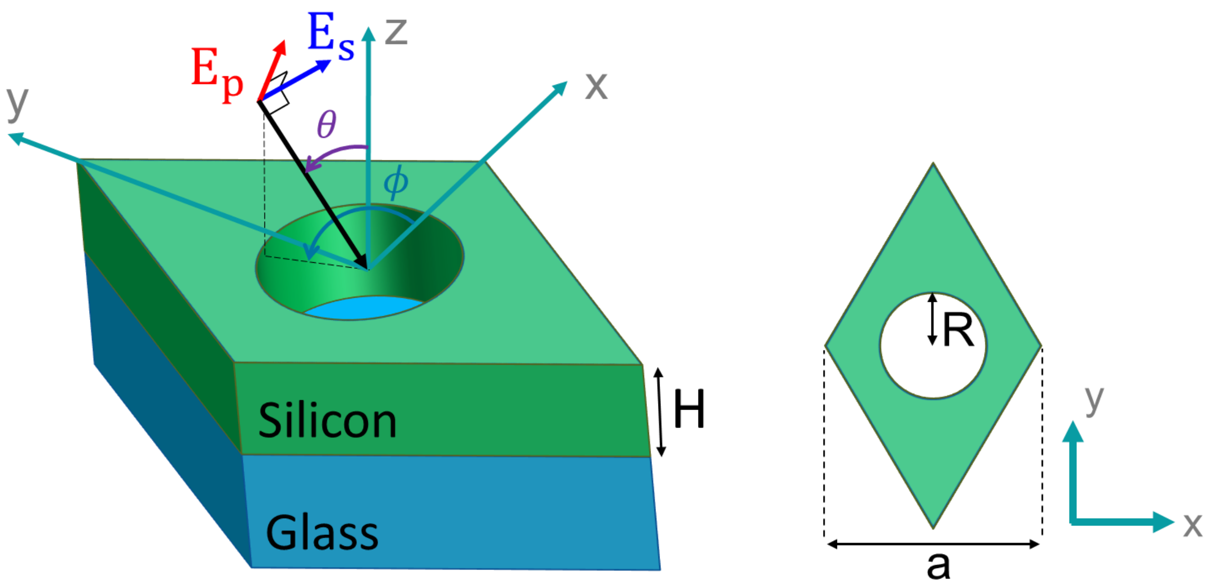
Our Approach: <u>Dispersion Engineering</u>

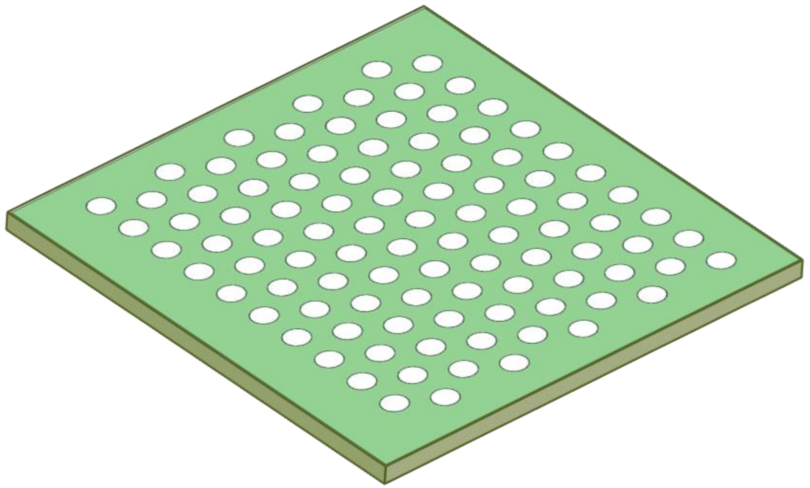


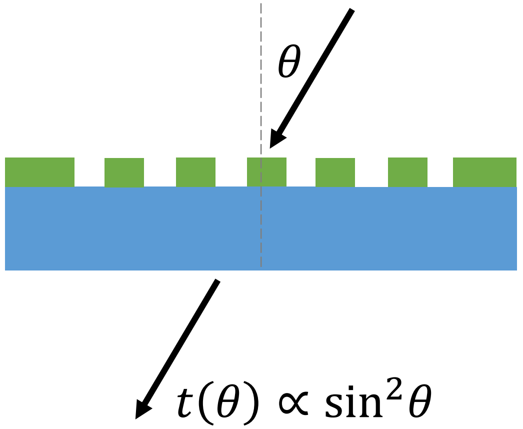
MC*, A. Arora*, S. Singh, A. Alù, *under review* (2023), **arXiv.2212.03468**

Broadband, High-Efficiency and High-NA Edge Detection

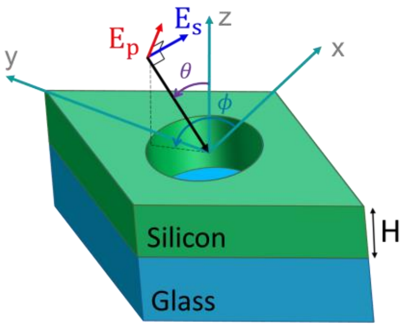
(amorphous) Silicon Metasurface on Glass





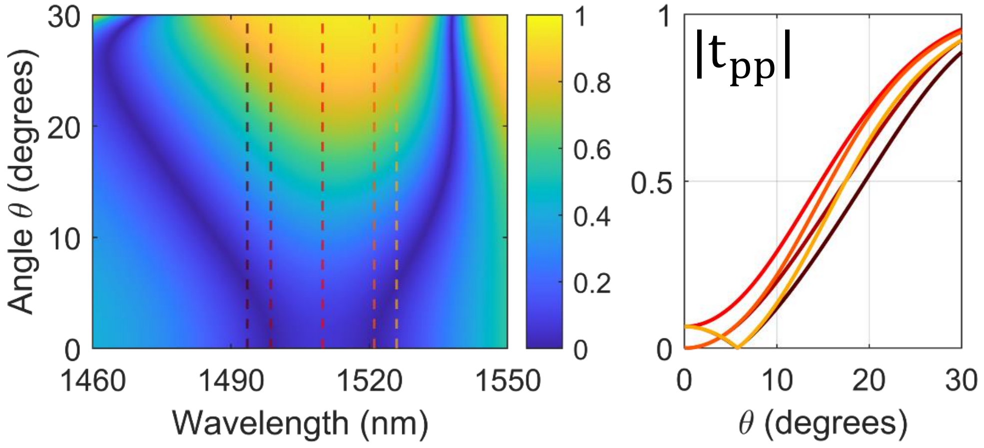


Broadband, High-Efficiency and High-NA Edge Detection



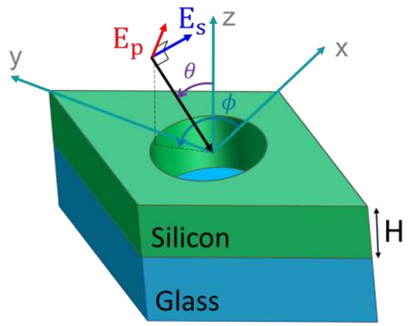
Calculations

$|t_{pp}|$



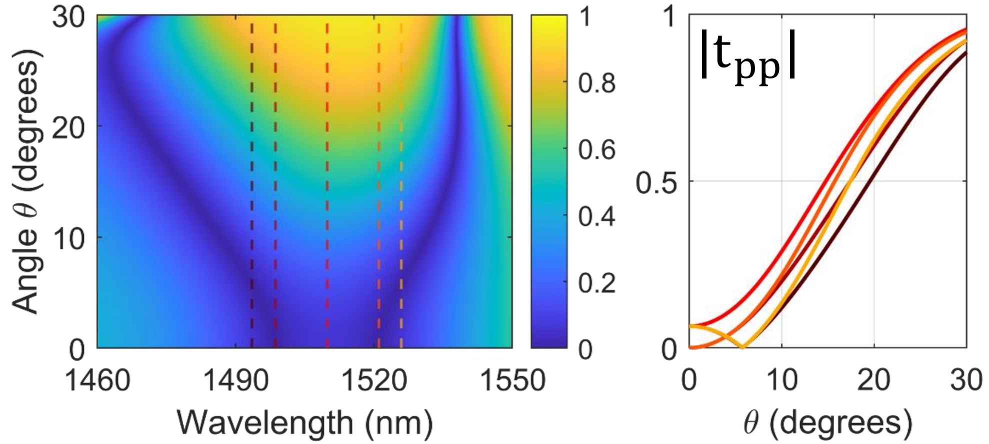
MC*, A. Arora*, S. Singh, A. Alù, *under review* (2023), **arXiv.2212.03468**

BROADBAND, HIGH-EFFICIENCY AND HIGH-NA EDGE DETECTION

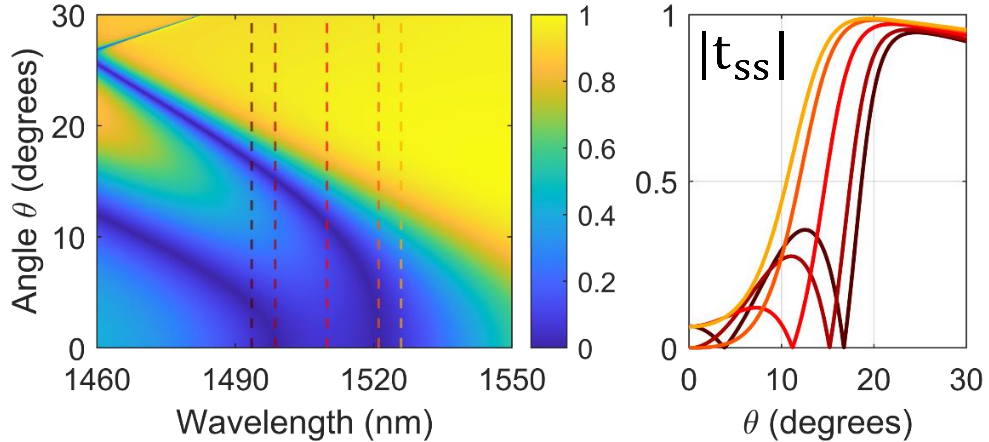


Calculations

$|t_{pp}|$

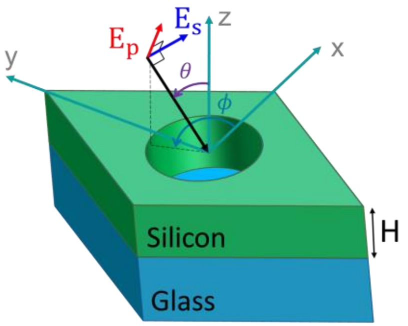


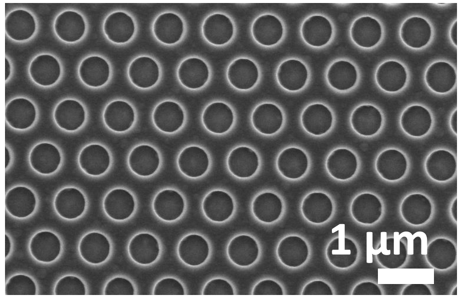
$|t_{ss}|$

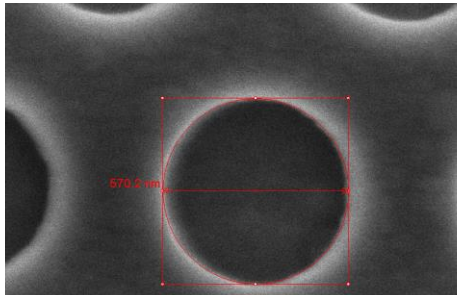


MC*, A. Arora*, S. Singh, A. Alù, *under review* (2023), **arXiv.2212.03468**

Broadband, High-Efficiency and High-NA Edge Detection



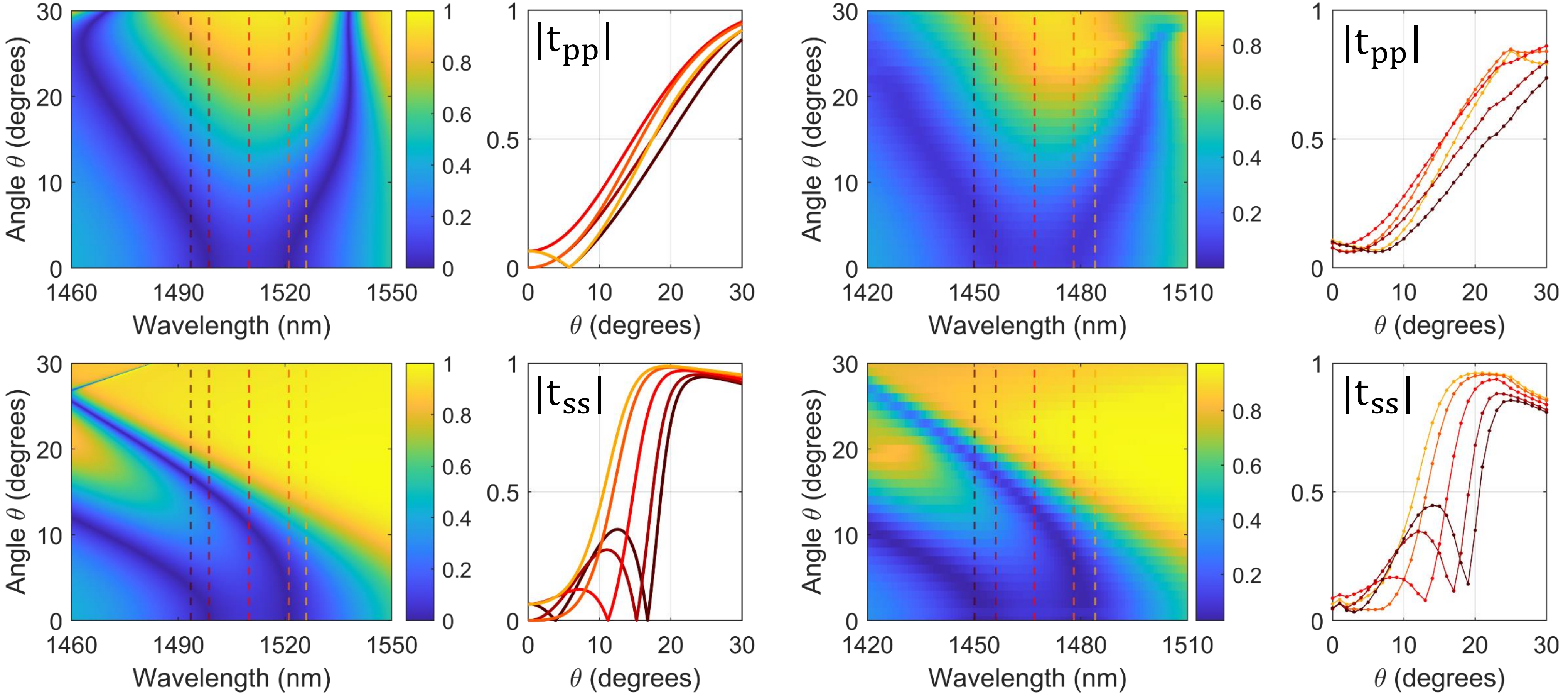




Calculations **Experiments**

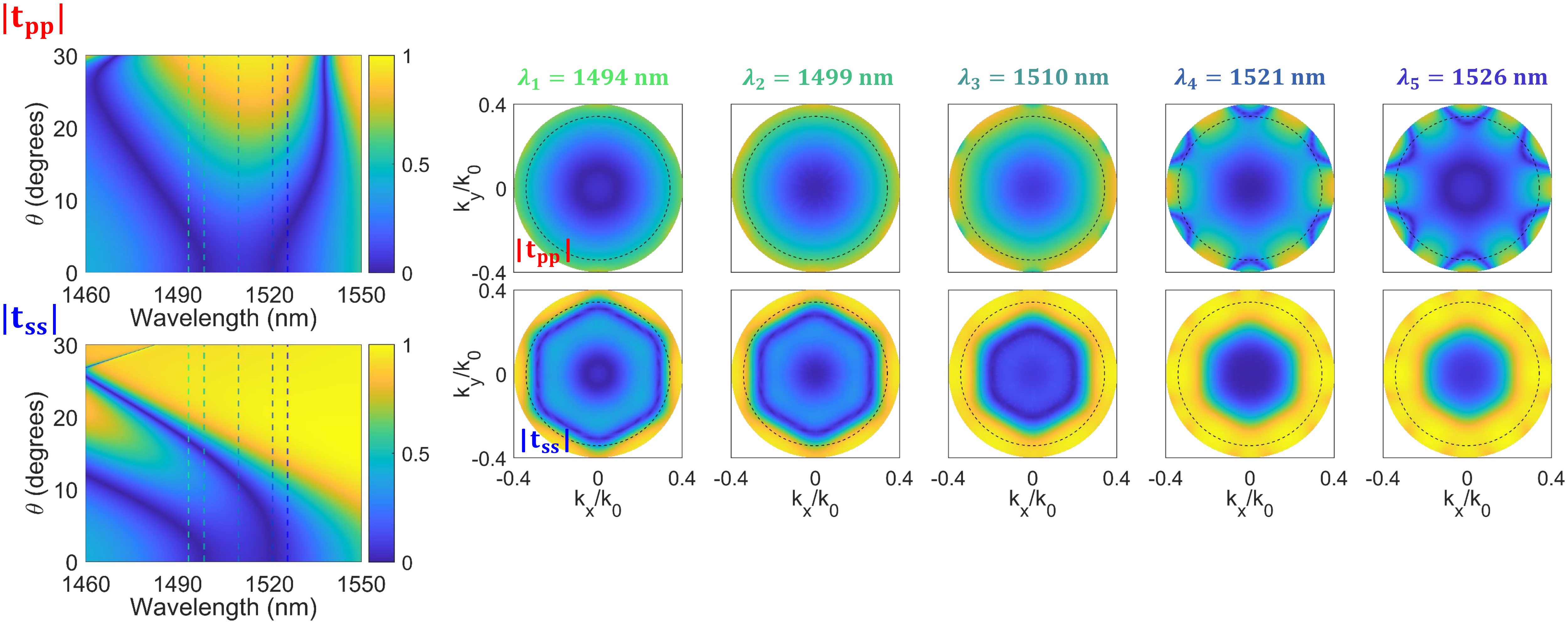
$|t_{pp}|$

$|t_{ss}|$



NA > 0.35

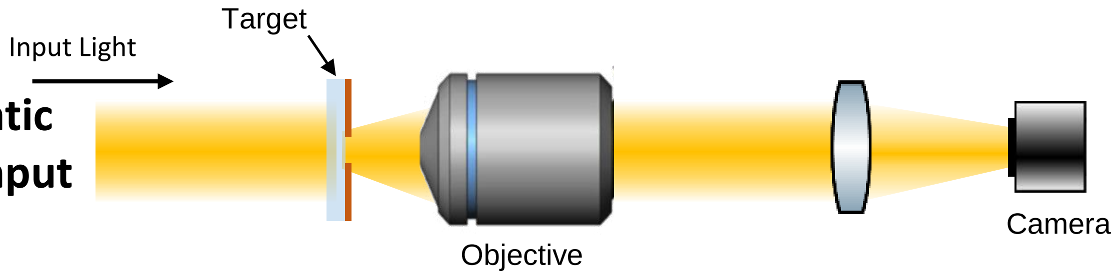
Broadband, High-Efficiency and High-NA Edge Detection



MC*, A. Arora*, S. Singh, A. Alù, *under review* (2023), **arXiv.2212.03468**

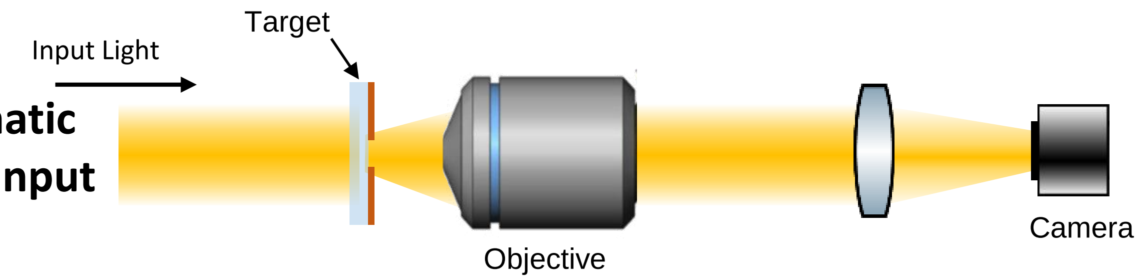
Broadband, High-Efficiency and High-NA Edge Detection

Monochromatic Unpolarized Input



Broadband, High-Efficiency and High-NA Edge Detection

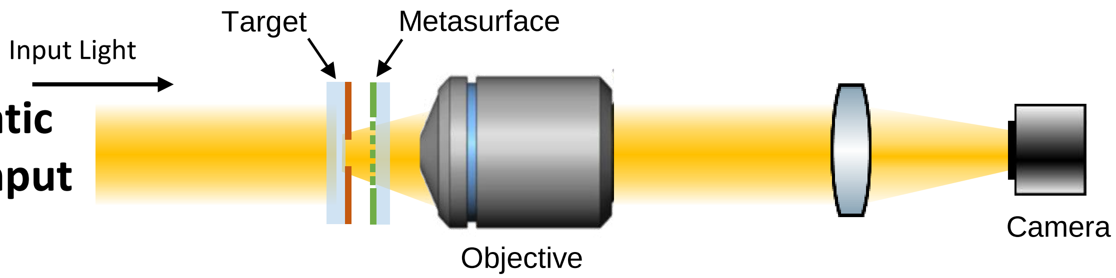
Monochromatic Unpolarized Input



MC*, A. Arora*, S. Singh, A. Alù, *under review* (2023), **arXiv.2212.03468**

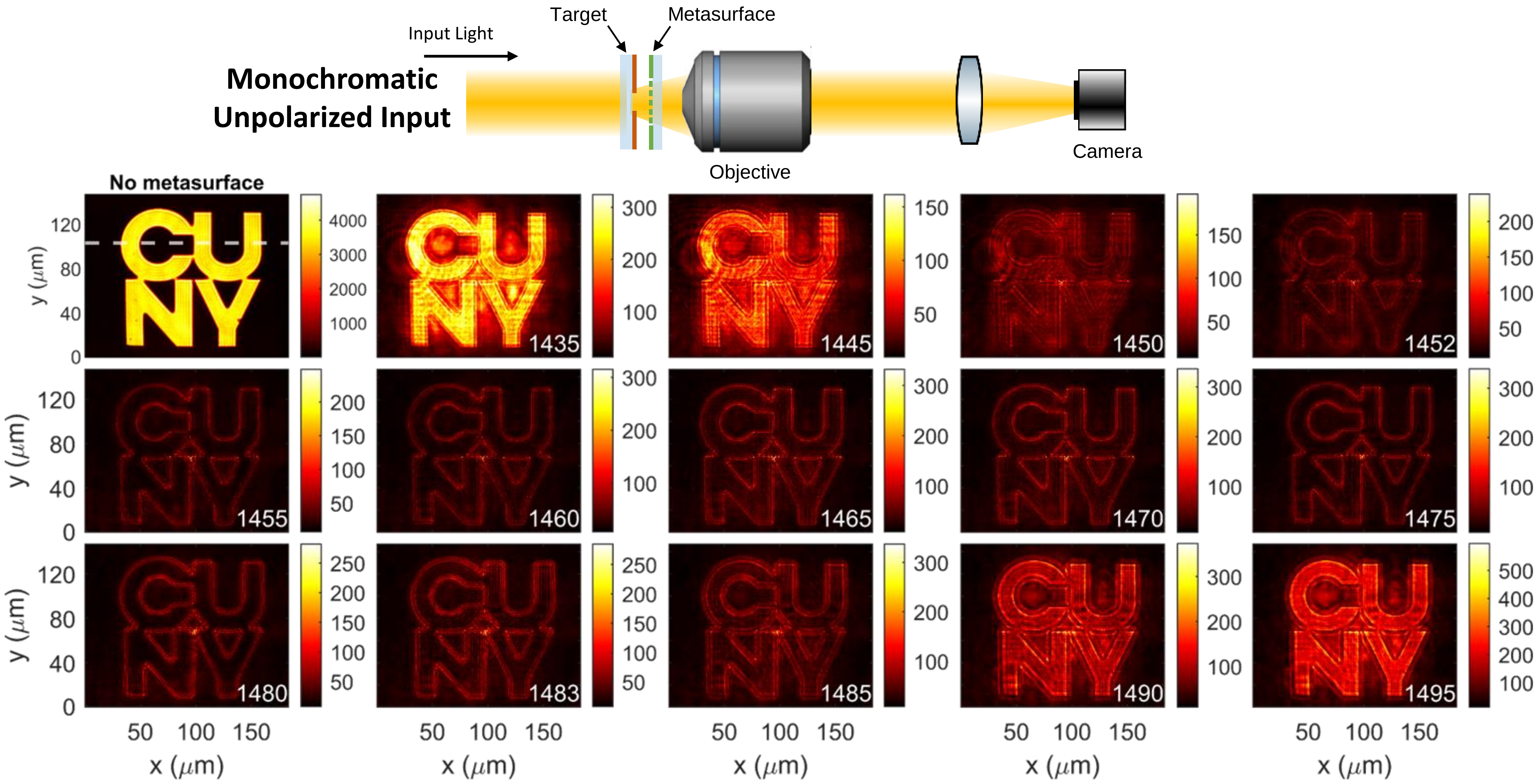
Broadband, High-Efficiency and High-NA Edge Detection

Monochromatic Unpolarized Input



MC*, A. Arora*, S. Singh, A. Alù, *under review* (2023), **arXiv.2212.03468**

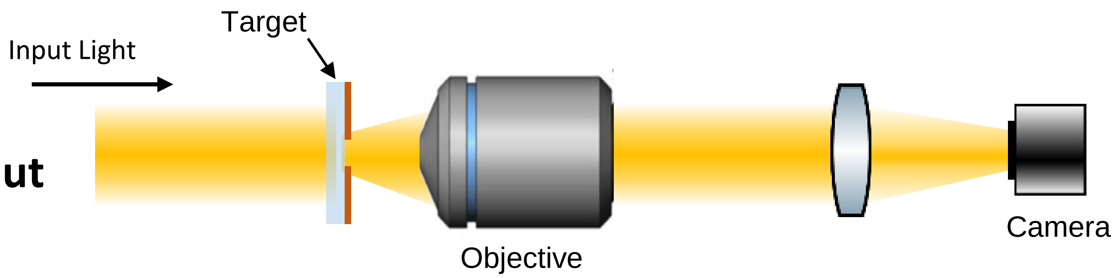
Broadband, High-Efficiency and High-NA Edge Detection

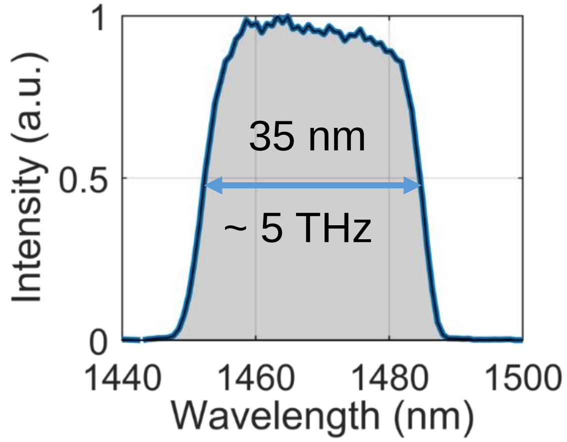


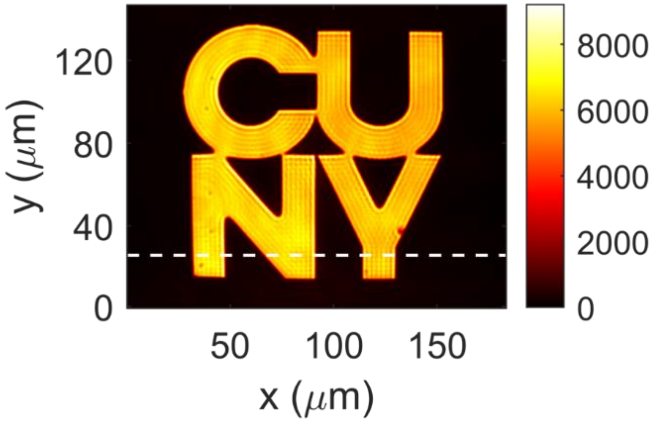
MC*, A. Arora*, S. Singh, A. Alù, *under review* (2023), arXiv.2212.03468

Broadband, High-Efficiency and High-NA Edge Detection

Polarized Broadband Input



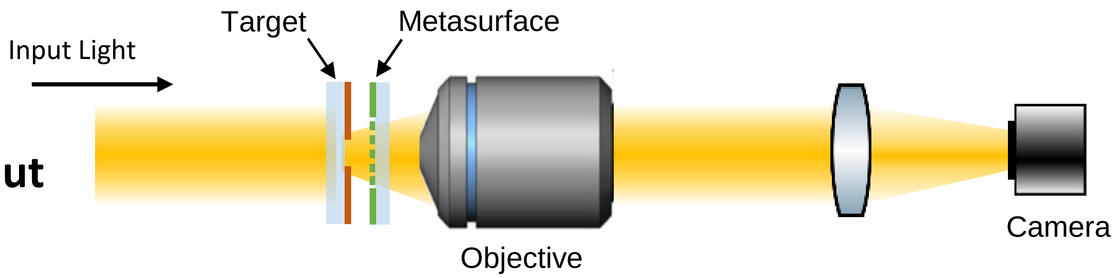


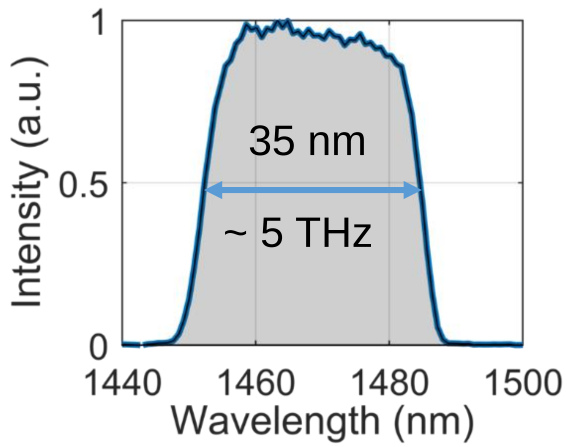


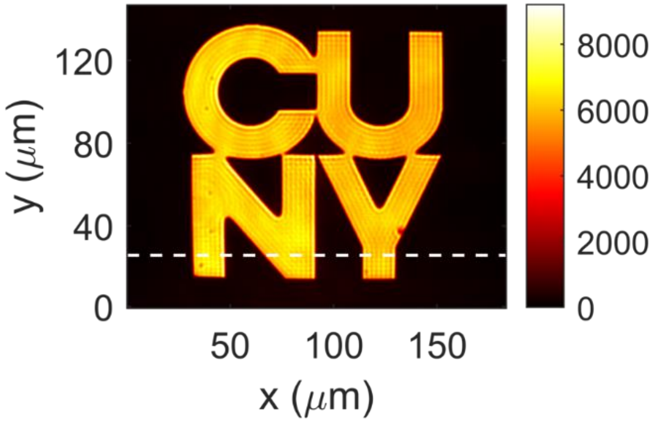
MC*, A. Arora*, S. Singh, A. Alù, *under review* (2023), **arXiv.2212.03468**

Broadband, High-Efficiency and High-NA Edge Detection

Polarized Broadband Input



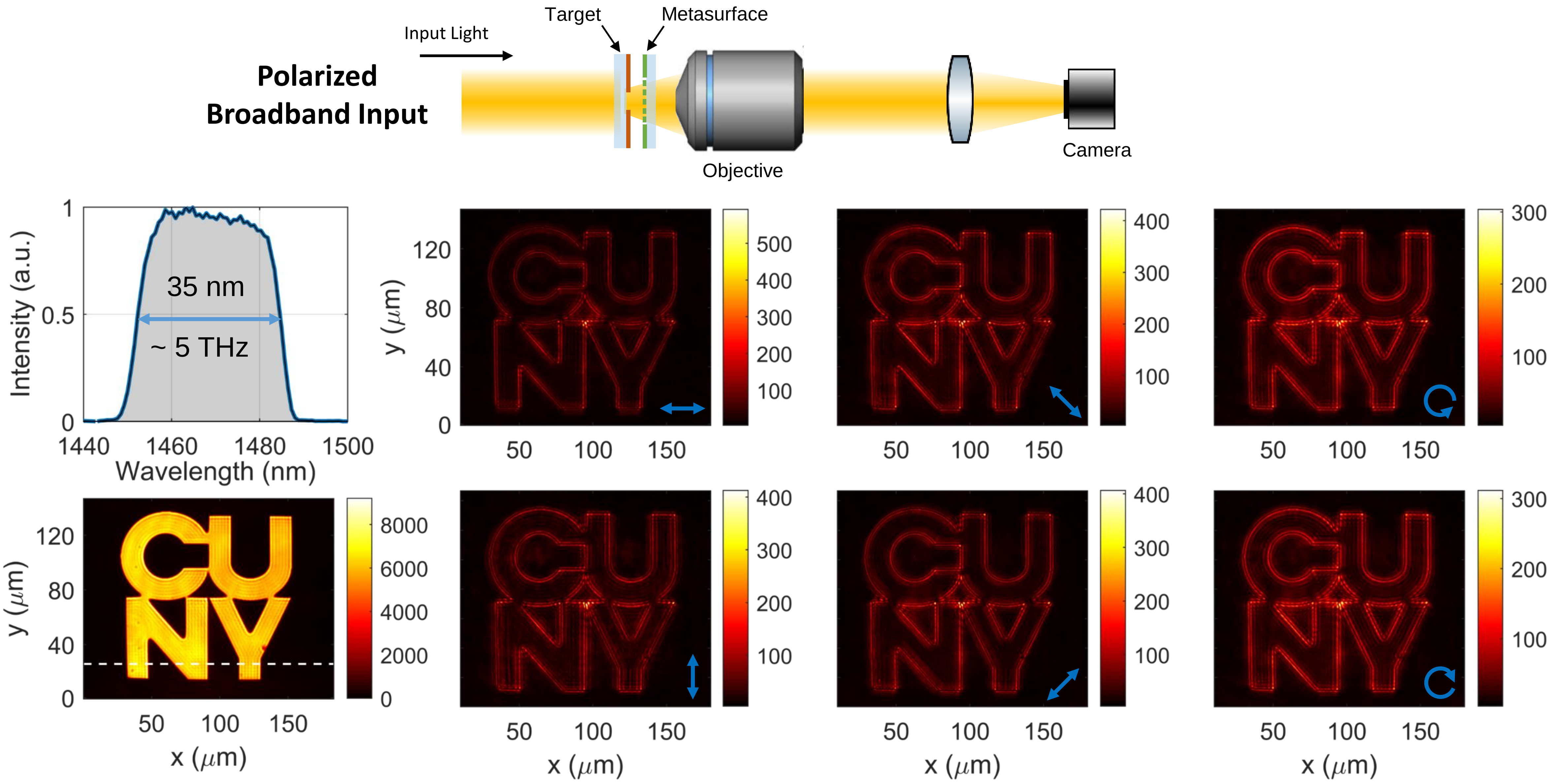




MC*, A. Arora*, S. Singh, A. Alù, *under review* (2023), **arXiv.2212.03468**

Broadband, High-Efficiency and High-NA Edge Detection

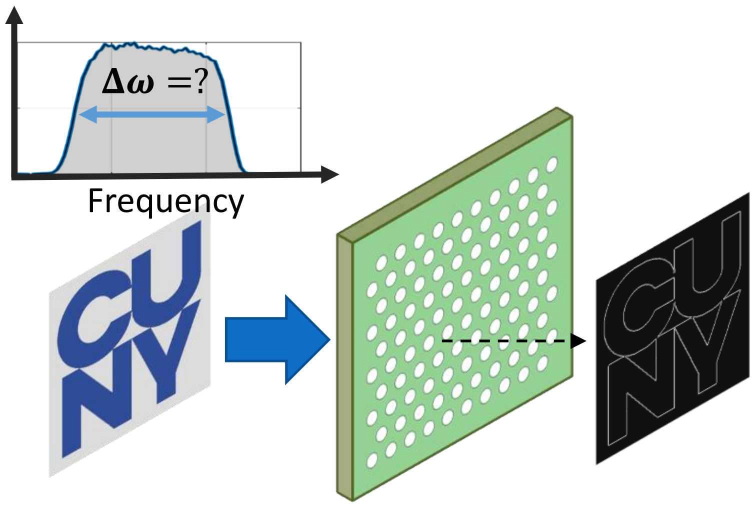
Polarized Broadband Input



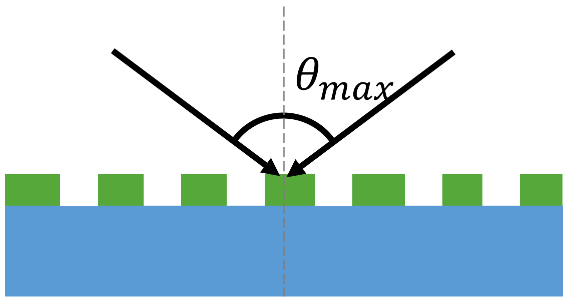
MC*, A. Arora*, S. Singh, A. Alù, *under review* (2023), **arXiv.2212.03468**

Important Figures of Merit

1. Spectral Bandwidth

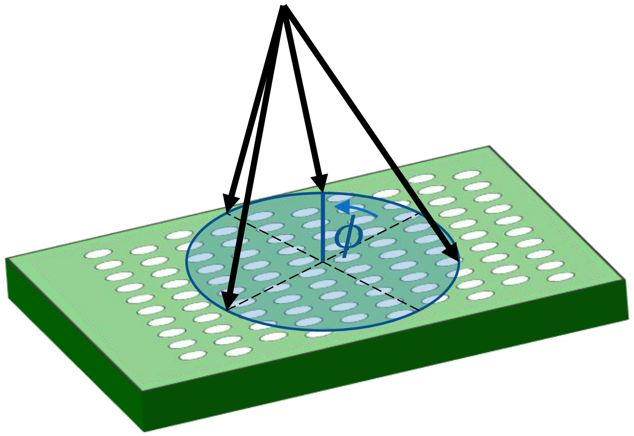


2. Numerical Aperture

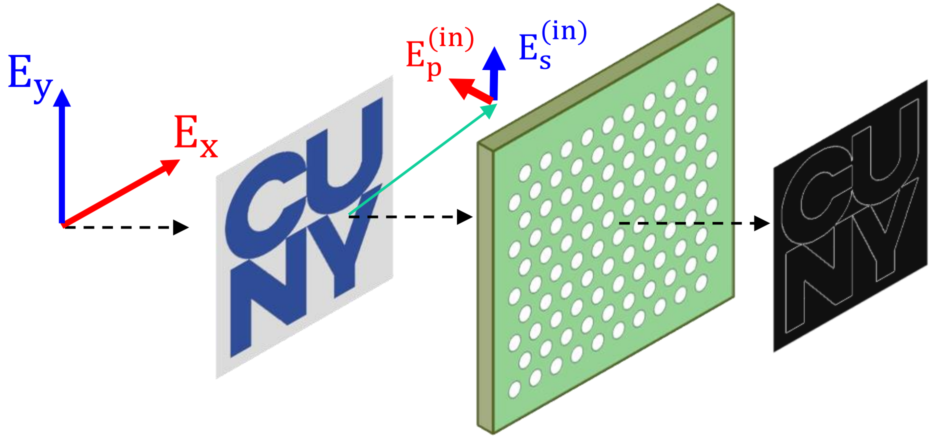


$NA = \sin\theta_{max}$

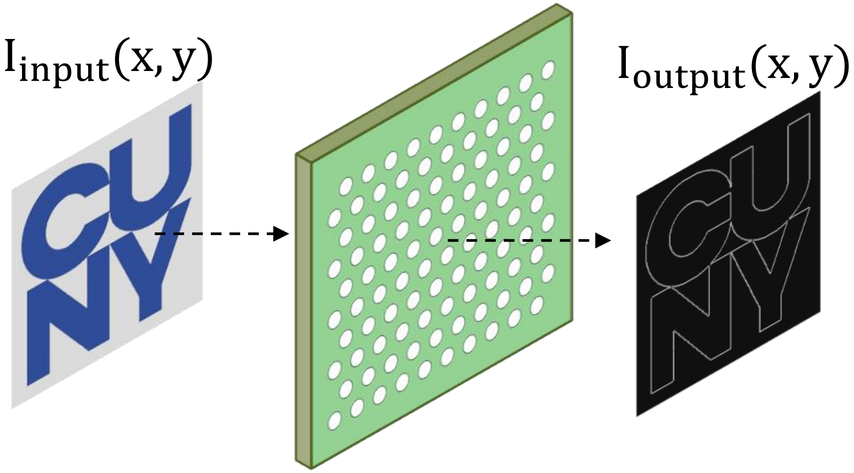
3. Azimuthal Isotropy



4. Polarization (in)dependence



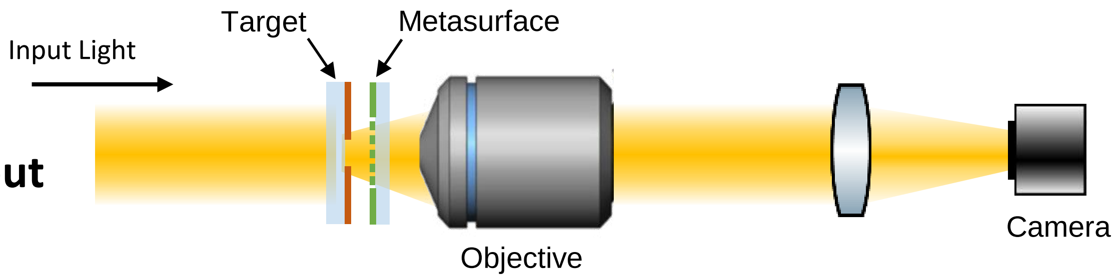
5. Efficiency

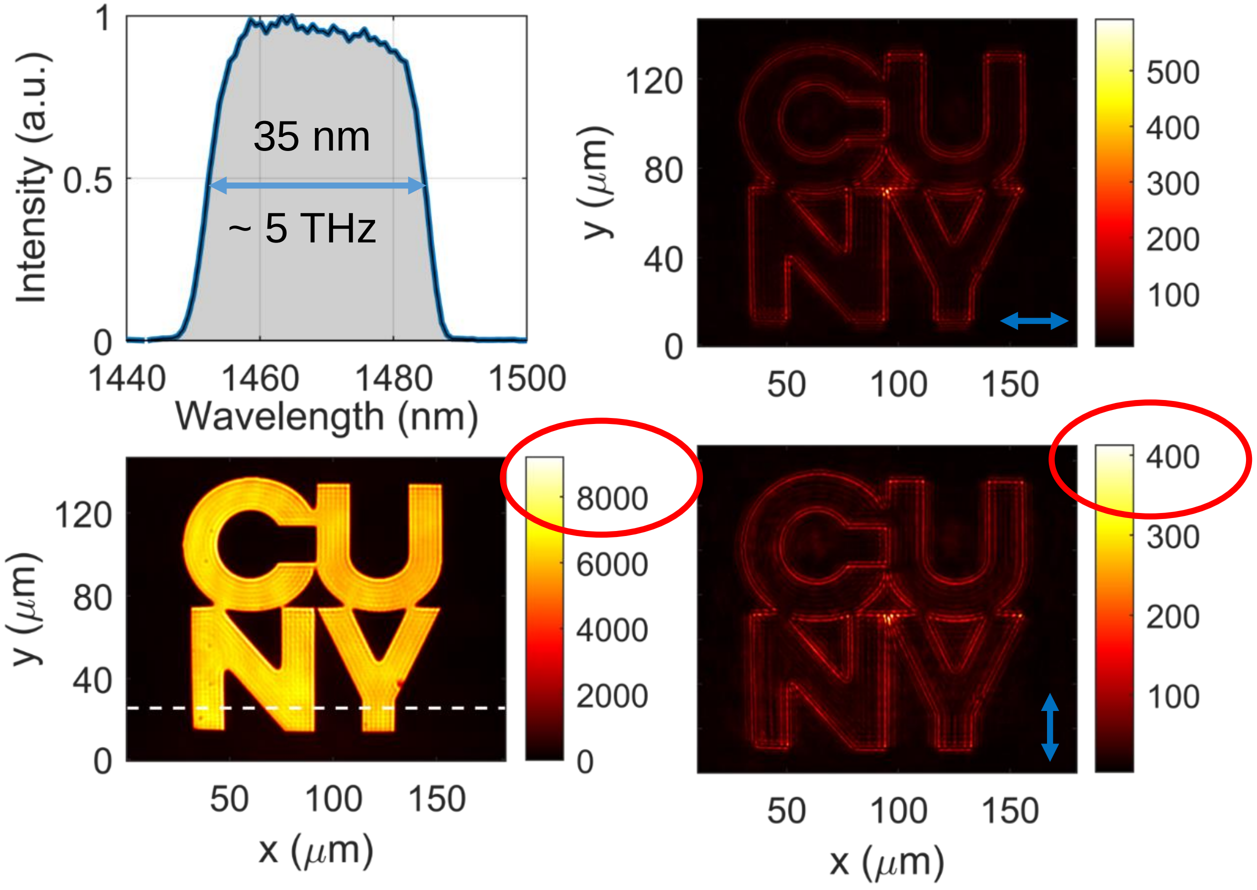


$\frac{I_{output}}{I_{input}} = ?$

BROADBAND, HIGH-EFFICIENCY AND HIGH-NA EDGE DETECTION

Polarized Broadband Input





In each measurement, counts are normalized by **camera integration time** and **laser power**

Efficiency:

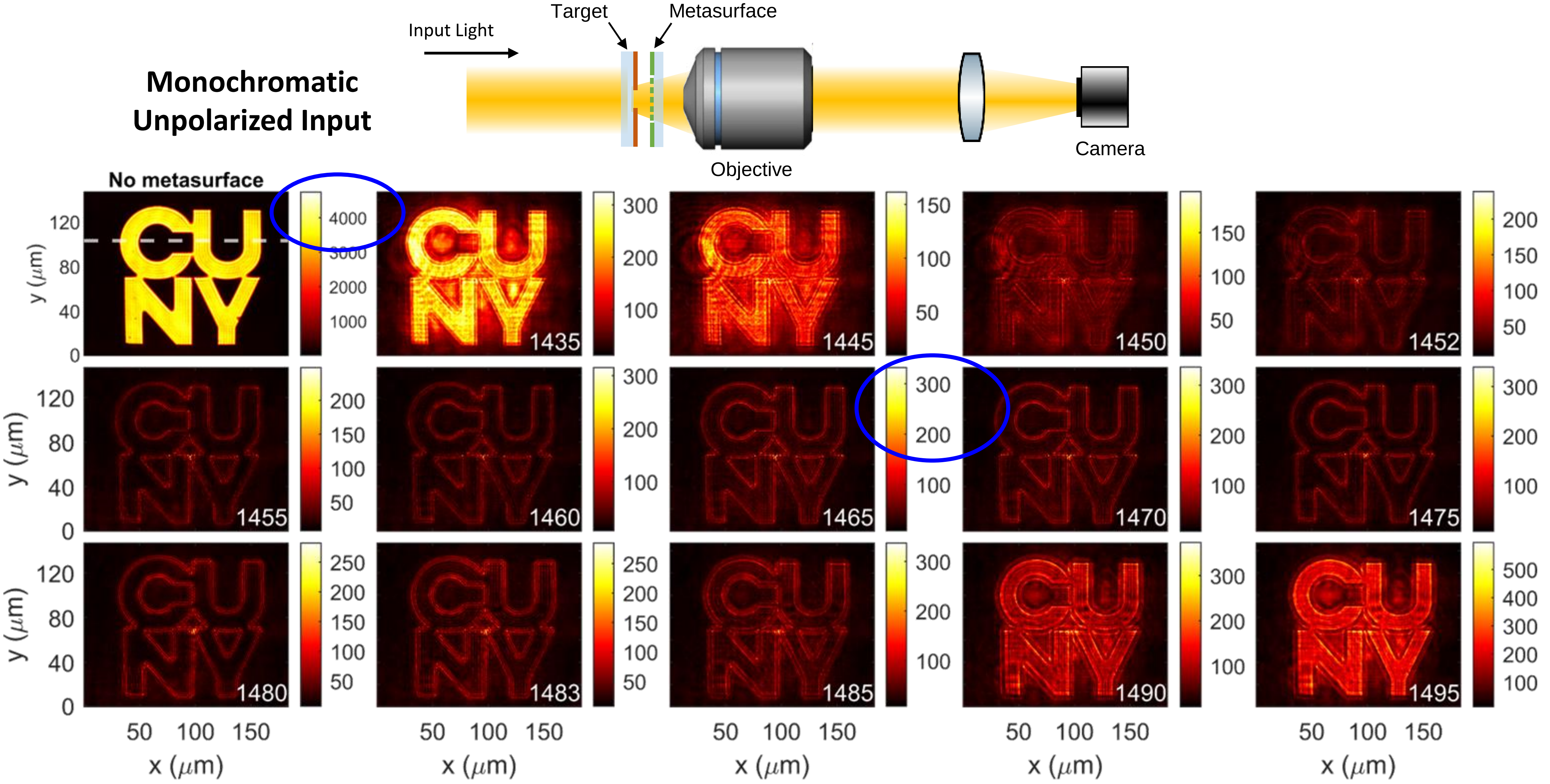
$$\eta_{peak} \equiv \frac{\max(I_{filtered})}{\max(I_{input})} \approx 4\% - 5\%$$

$$\eta_{avg} \equiv \frac{\text{avg}_{\text{edge}}(I_{filtered})}{\max(I_{input})} \approx 1 - 2\%$$

MC*, A. Arora*, S. Singh, A. Alù, *under review* (2023), **arXiv.2212.03468**

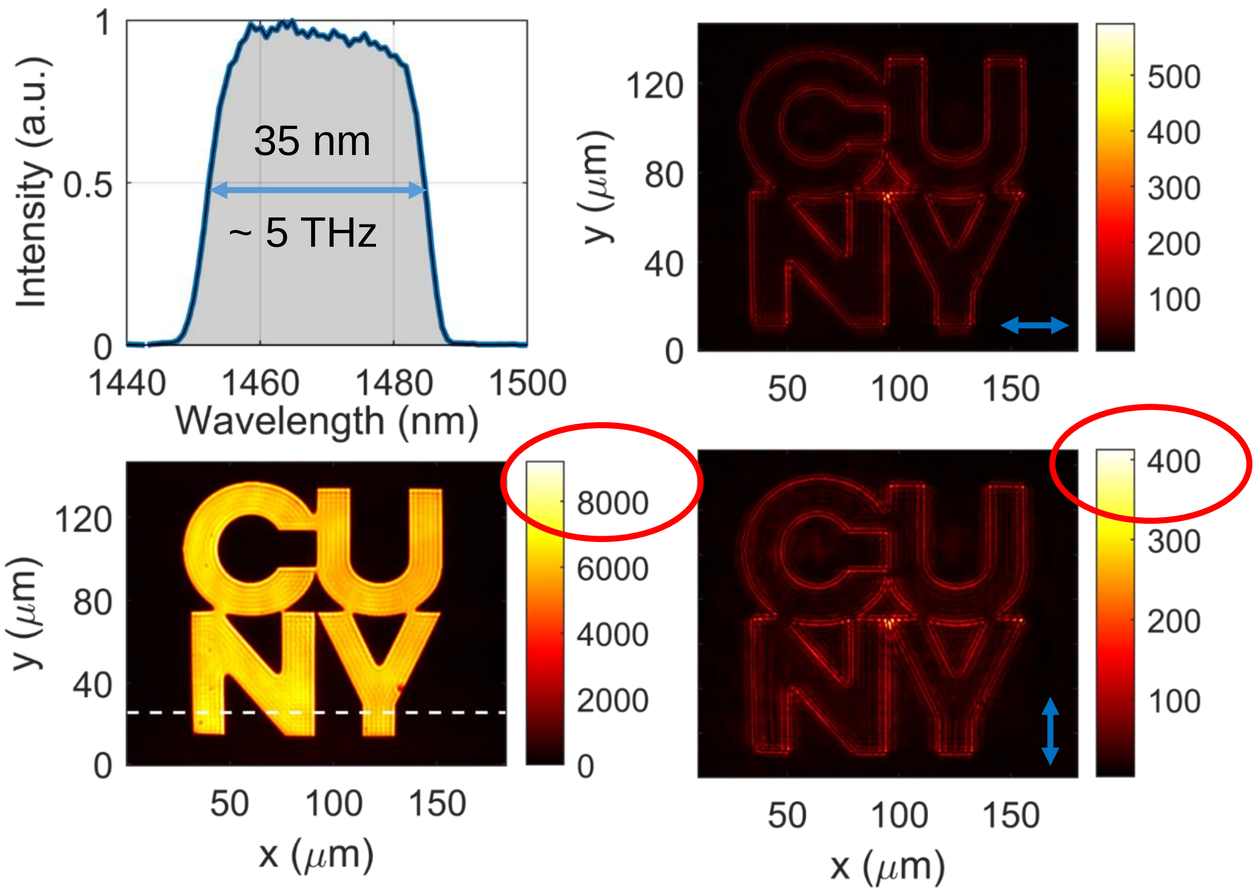
BROADBAND, HIGH-EFFICIENCY AND HIGH-NA EDGE DETECTION

Monochromatic Unpolarized Input



MC*, Akshaj Arora*, Sahitya Singh, Andrea Alù, *under review* (2023), **arXiv.2212.03468**

Broadband, High-Efficiency and High-NA Edge Detection



Efficiency:

$$\eta_{peak} \equiv \frac{\max(I_{filtered})}{\max(I_{input})} \approx 4\% - 5\%$$

$$\eta_{avg} \equiv \frac{\mathrm{avg}_{\mathrm{edge}}(I_{filtered})}{\max(I_{input})} \approx 1 - 2\%$$

How good are these efficiencies?

- Efficiencies of 1% - 5% sound small…
- (Reviewers do not seem to like 1-digit numbers)

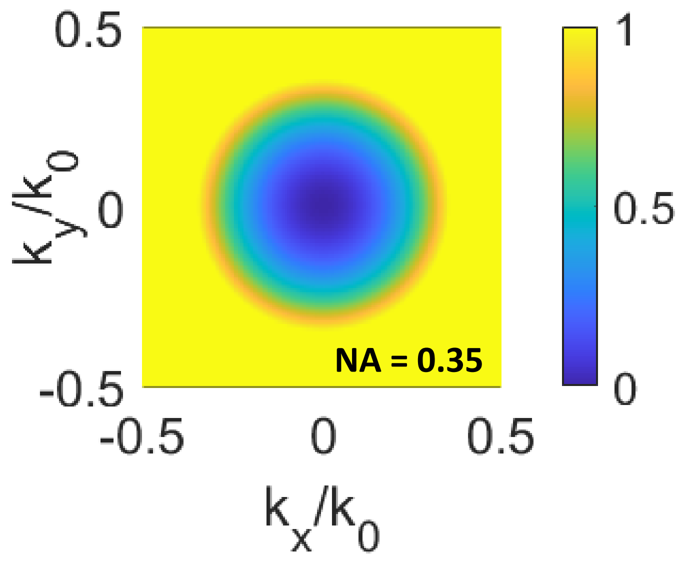
MC*, A. Arora*, S. Singh, A. Alù, *under review* (2023), **arXiv.2212.03468**

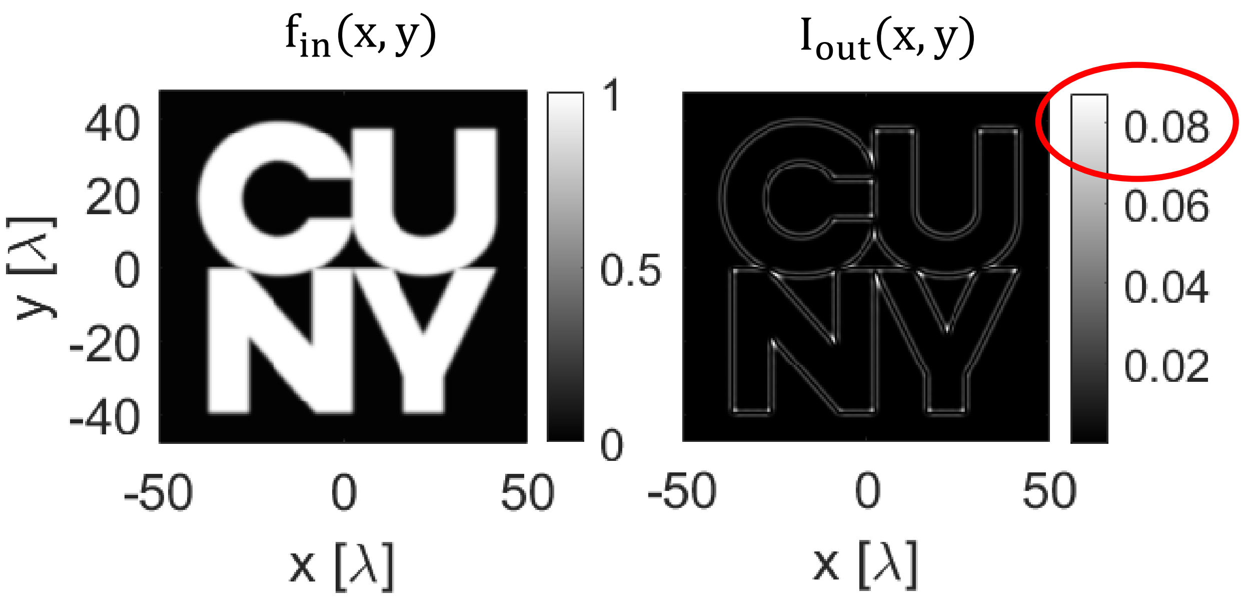
Comparison with Ideal Edge Detector

How good are these efficiencies?

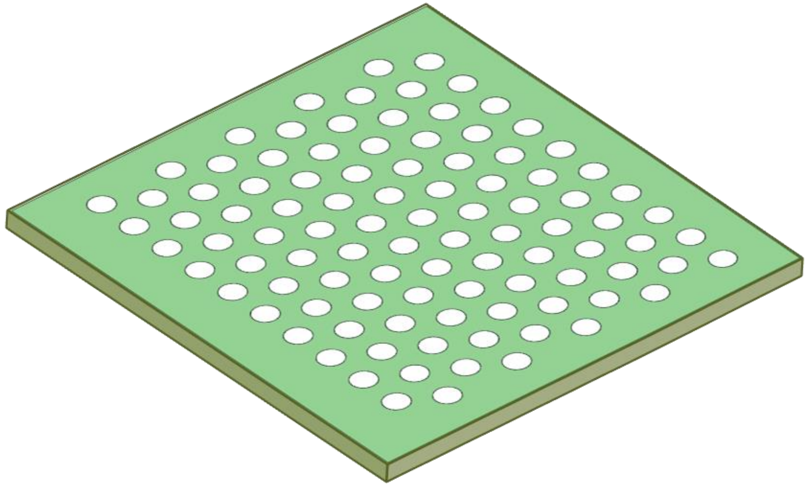
$$t_{pp}(k_x,k_y) = t_{ss}(k_x,k_y) = t_{ideal}(k_x,k_y) = \begin{cases} \left(\frac{1}{k_0^2 NA^2}\right)\cdot\left(k_x^2+k_y^2\right) & \text{if } k_x^2+k_y^2 \le k_0^2 NA^2 \\ 1 & \text{otherwise} \end{cases}$$

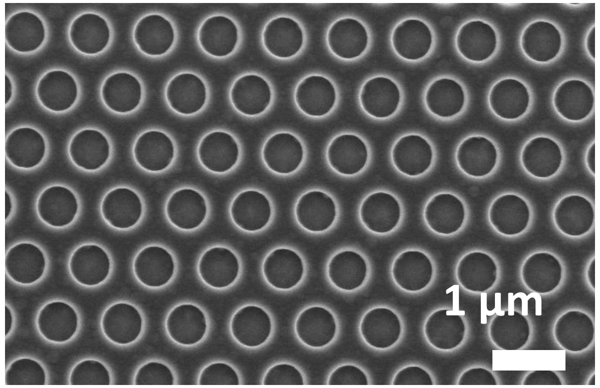
Ideal Detector

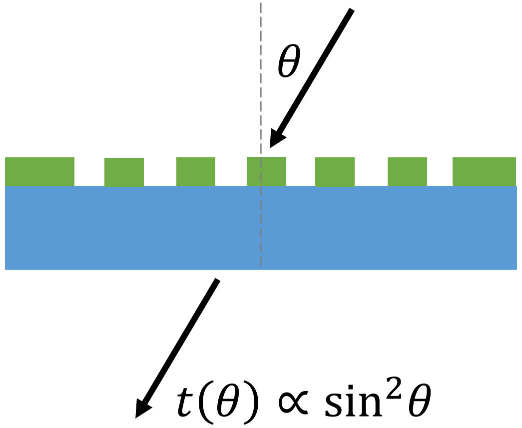




Simultaneous Optimization of All Figures Of Merit



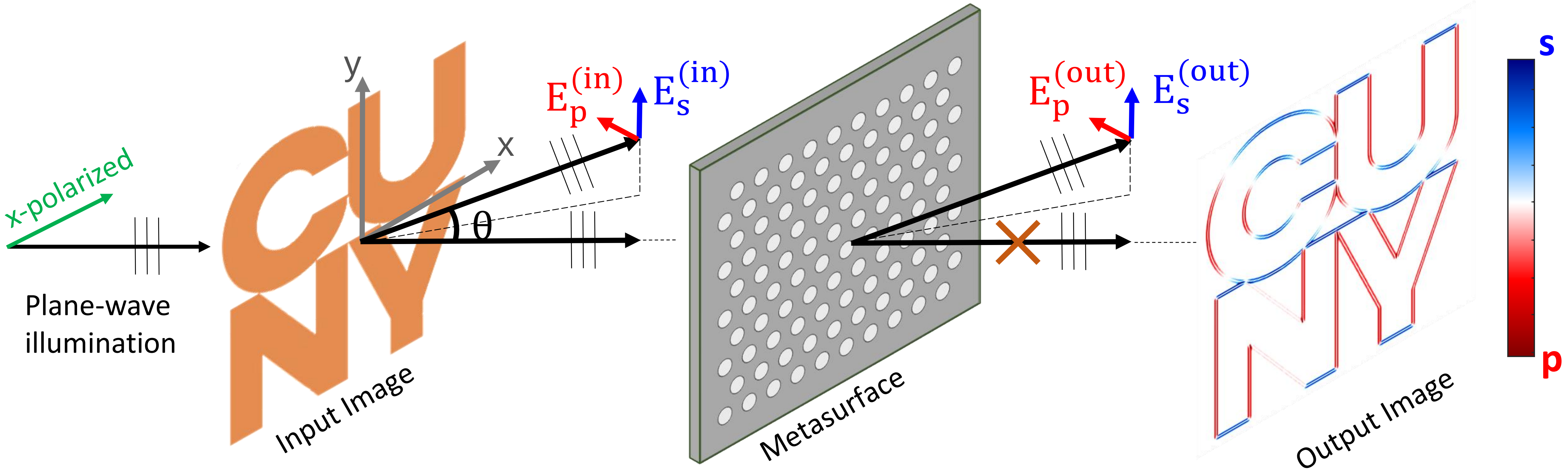




- **Full Polarization-Independent**
- **High NA** (NA > 0.35)
- **Large bandwidths**
  ($\Delta\lambda \geq 35\, nm$ @ $1500\, nm$)
- **Very high Efficiencies**
  Close to the maximum allowed by math!
- **High Isotropy**
  C6 symmetry → Largest isotropy allowed by a period metasurface

MC*, A. Arora*, S. Singh, A. Alù, *under review* (2023), **arXiv.2212.03468**

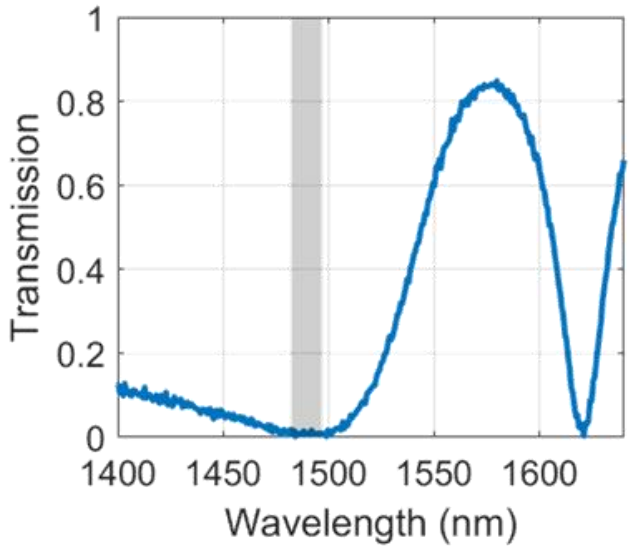
Polarization-Dependent Edge-Detection



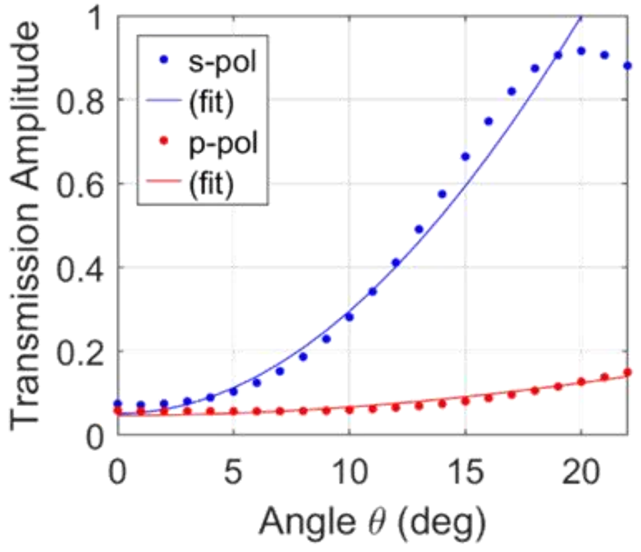
MC*, S. Singh*, A. Arora, A. Alù, *in preparation* (2023)

Single-Polarization Metasurface

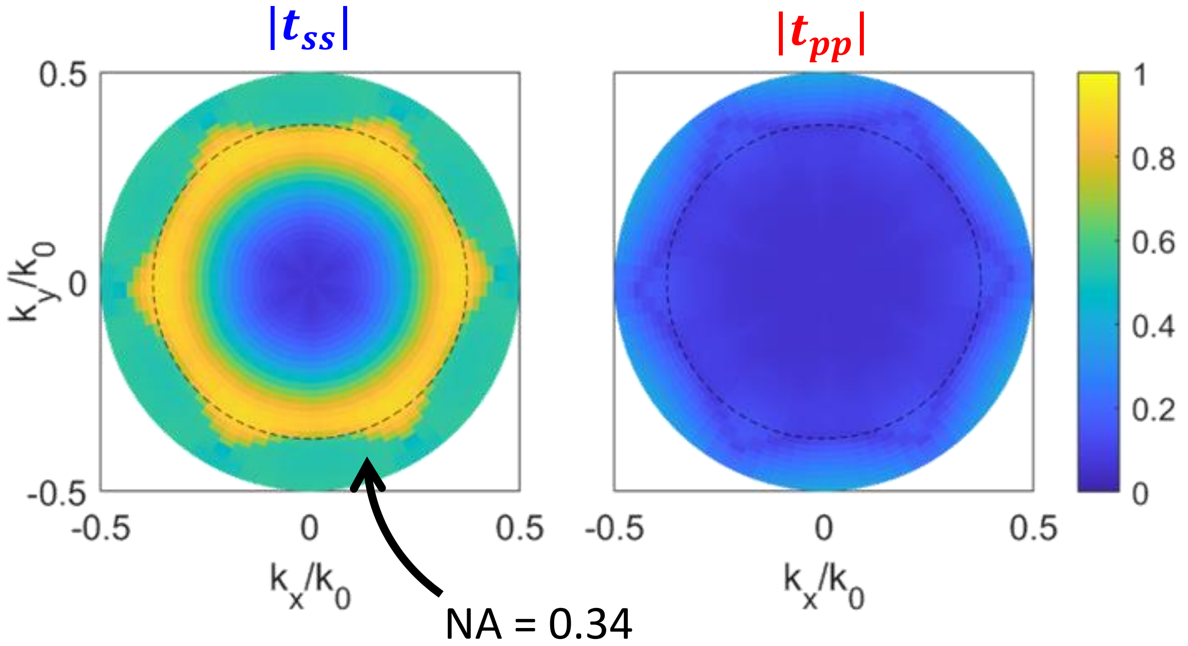
Normal-incidence transmission

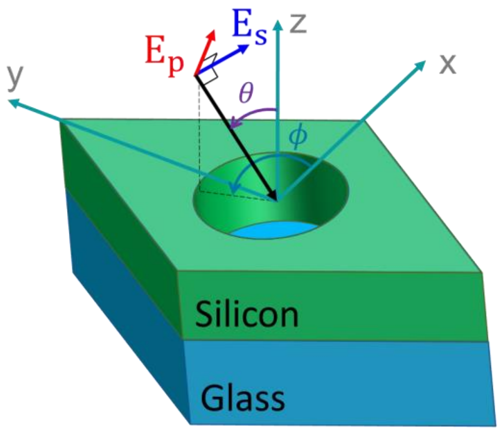


Measured $|t_{ss}|$ and $|t_{pp}|$



Measured transfer functions

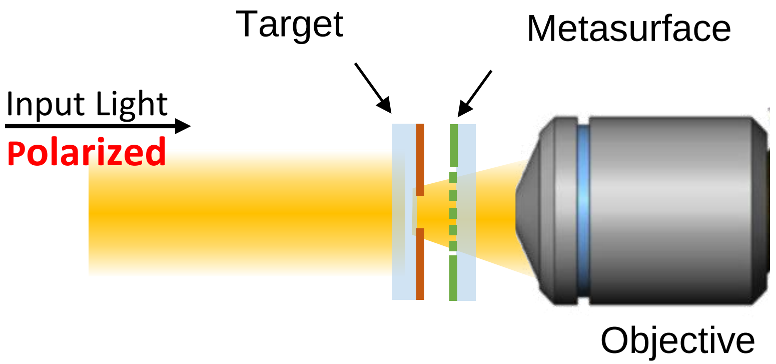




Same metasurface pattern as before (i.e. same C_6 symmetry) but different geometrical parameters

MC*, S. Singh*, A. Arora, A. Alù, *in preparation* (2023)

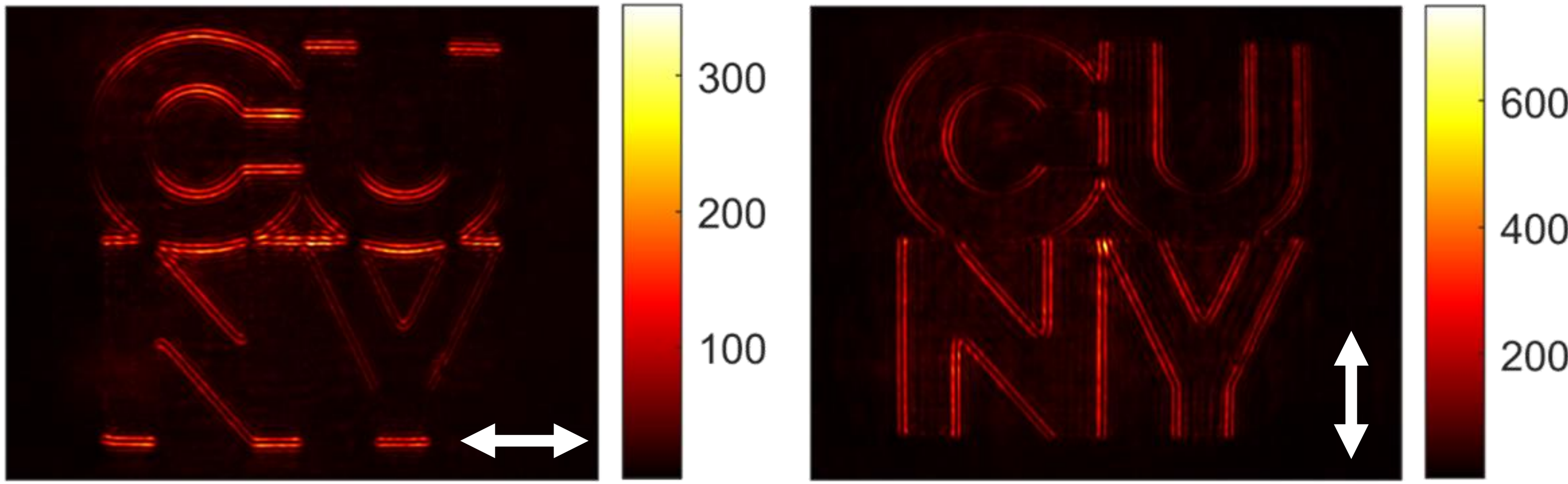
Polarization-Dependent Edge Detection



Unfiltered image

Scale bar = 30 µm

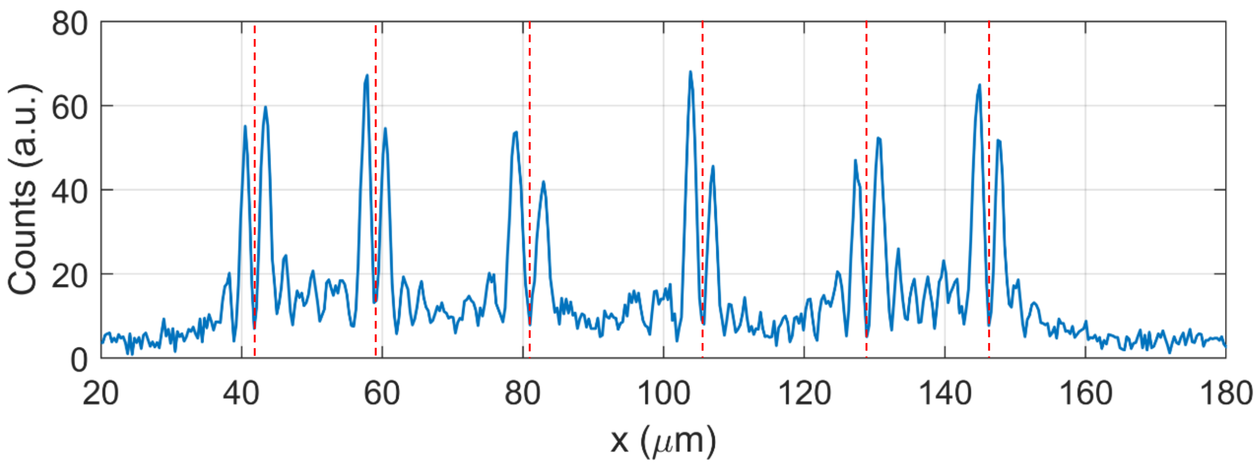
Direction-Dependent Edge Detection

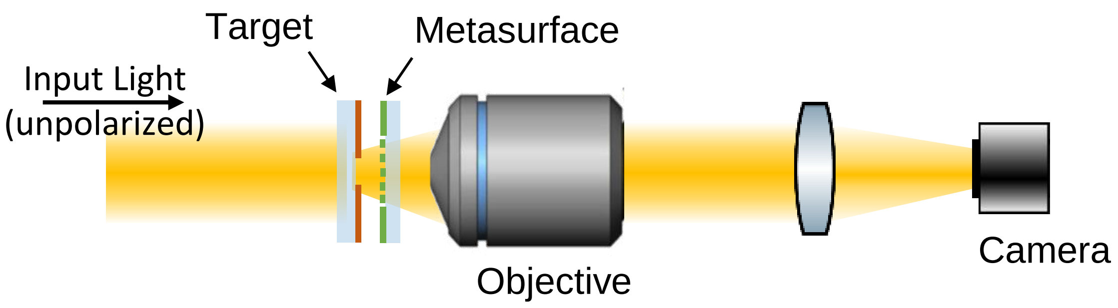


$\eta_{peak} > 3\ \%$

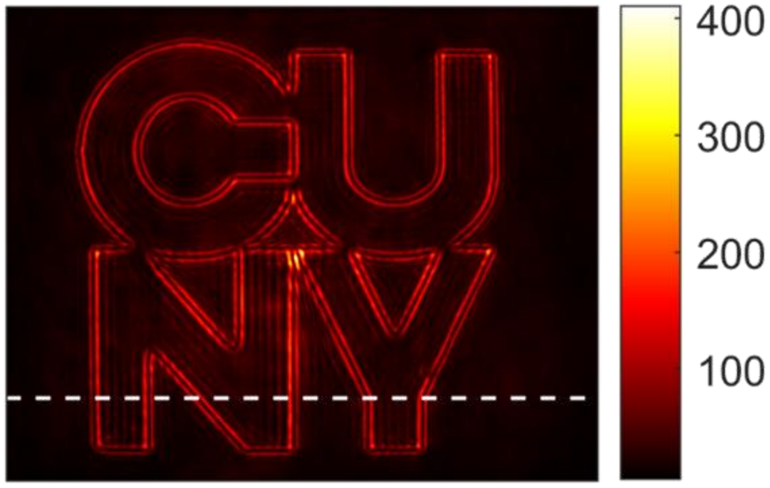
MC*, S. Singh*, A. Arora, A. Alù, *in preparation* (2023)

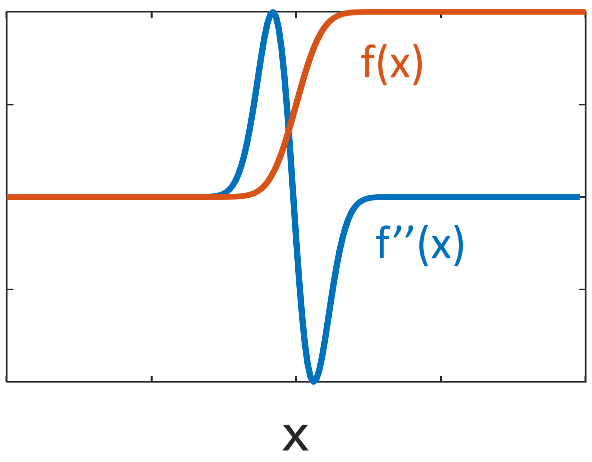
Second-Order Derivative





Filtered image, unpolarized excitation





MC*, S. Singh*, A. Arora, A. Alù, *in preparation* (2023)

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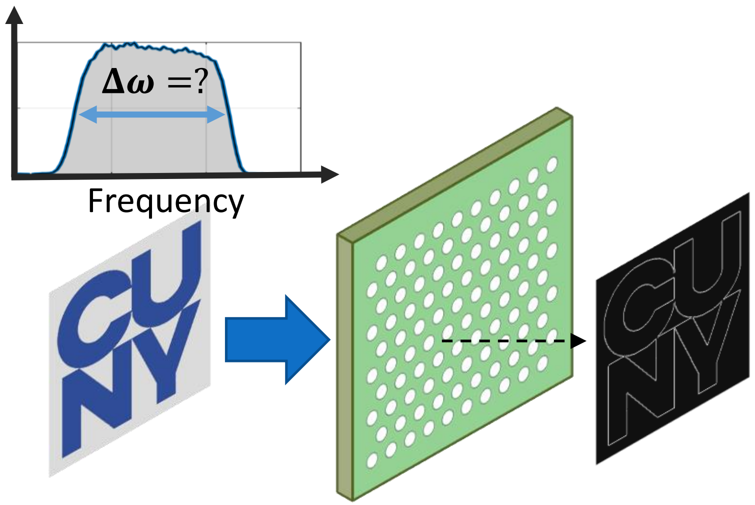

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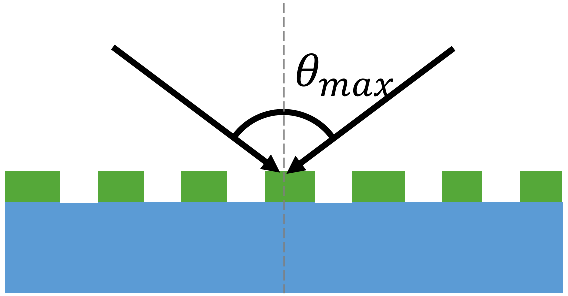
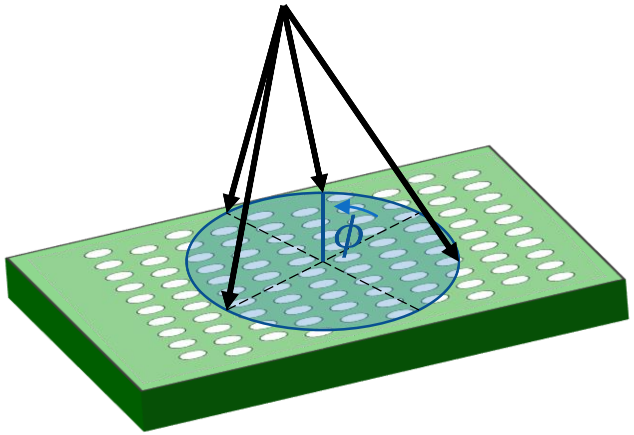


$NA = \sin\theta_{max}$

3. Azimuthal Isotropy



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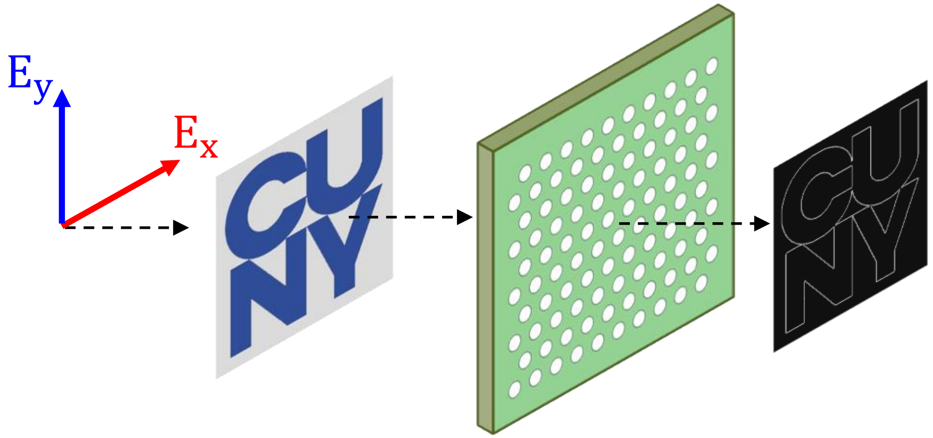
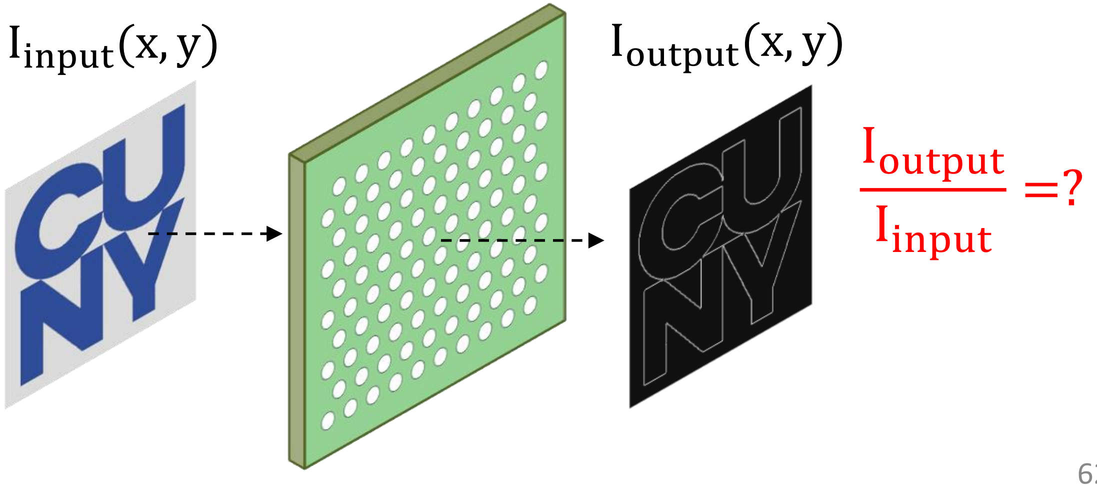
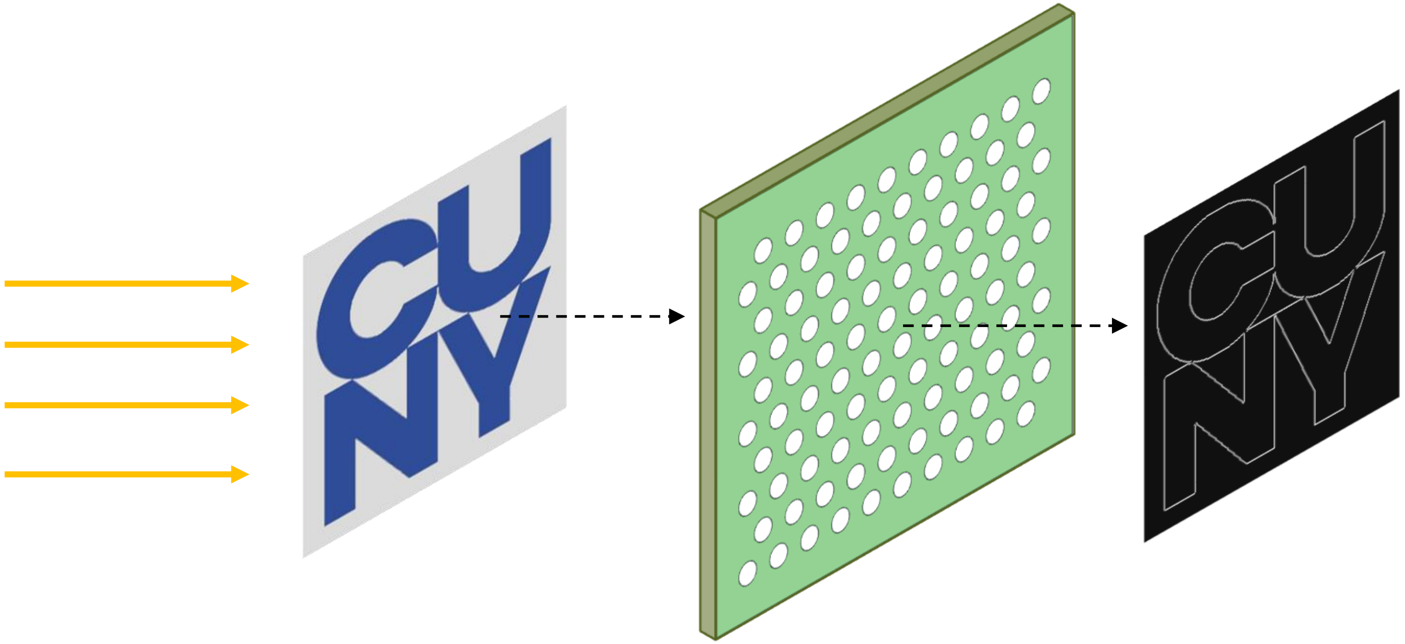


5. Efficiency



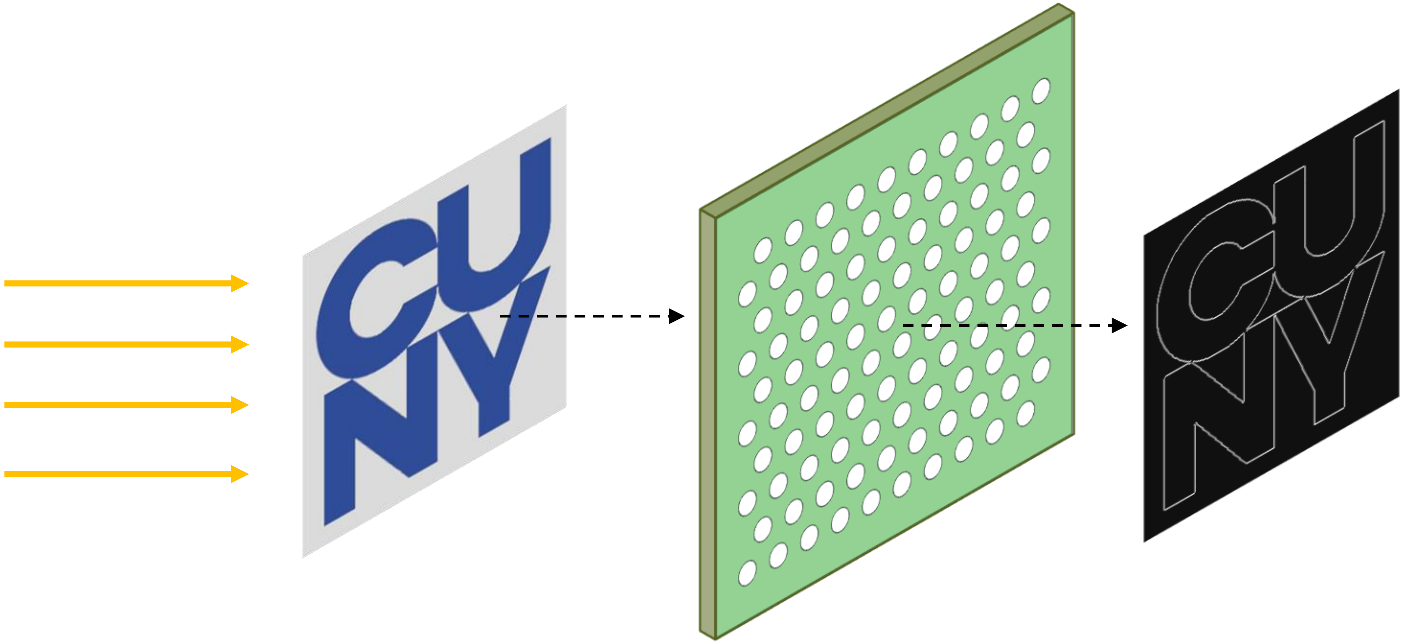
COHERENT VS INCOHERENT ILLUMINATION



- The image processing is obtained via coherent superposition of several waves diffracted by the image
- The input illumination must have some degree of <u>spatial coherence</u>

- Wang et a;, *Compact incoherent image differentiation with nanophotonic structures*. **ACS Photonics**, *7*(2), pp.338-343 (2020)
- Zhang et al. *Incoherent Optoelectronic Differentiation Based on Optimized Multilayer Films.* **Laser & Photonics Reviews** 16.9 : 2200038 (2022)

Coherent vs Incoherent Illumination



Coherent illumination:
we can manipulate the field amplitude

$$E_{in}(\mathbf{k}_{\parallel}) \rightarrow E_{out}(\mathbf{k}_{\parallel}) = t(\mathbf{k}_{\parallel})E_{in}(\mathbf{k}_{\parallel})$$

Transmission amplitude

$$t(\mathbf{k}_{\parallel}) \propto |\mathbf{k}_{\parallel}|^2$$

Incoherent illumination:
we need to work “directly” with the intensity

$$I_{in}(\mathbf{k}_{\parallel}) \rightarrow I_{out}(\mathbf{k}_{\parallel}) = T(\mathbf{k}_{\parallel})I_{in}(\mathbf{k}_{\parallel})$$

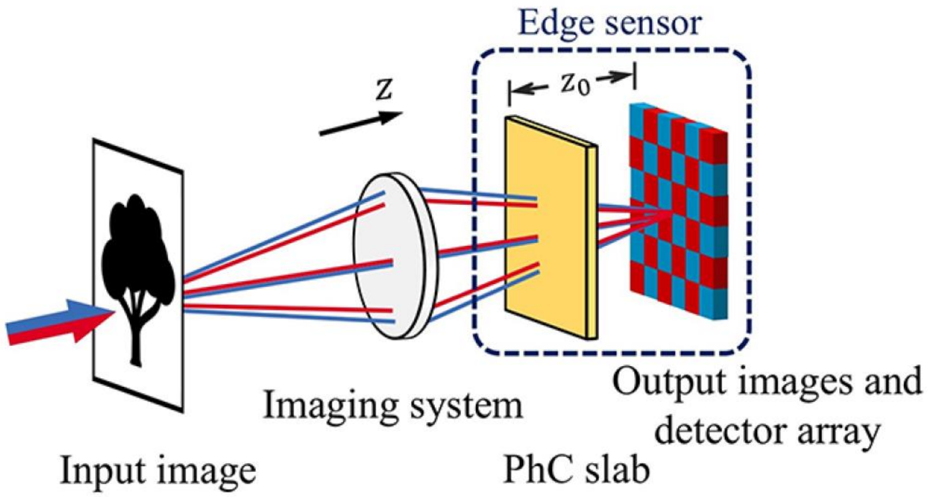
Can we get $T(\mathbf{k}_{\parallel}) \propto |\mathbf{k}_{\parallel}|^2$?

$T(\mathbf{k}_{\parallel}) \propto \int t^*(\boldsymbol{q})t(\boldsymbol{k}_{\parallel} + \boldsymbol{q})d\boldsymbol{q}$ ⇨ $T(\mathbf{k}_{\parallel})$ always maximizes at $\mathbf{k}_{\parallel} = \mathbf{0}$

- Wang et a;, *Compact incoherent image differentiation with nanophotonic structures*. **ACS Photonics**, *7*(2), pp.338-343 (2020)
- Zhang et al. *Incoherent Optoelectronic Differentiation Based on Optimized Multilayer Films.* **Laser & Photonics Reviews** 16.9 : 2200038 (2022)

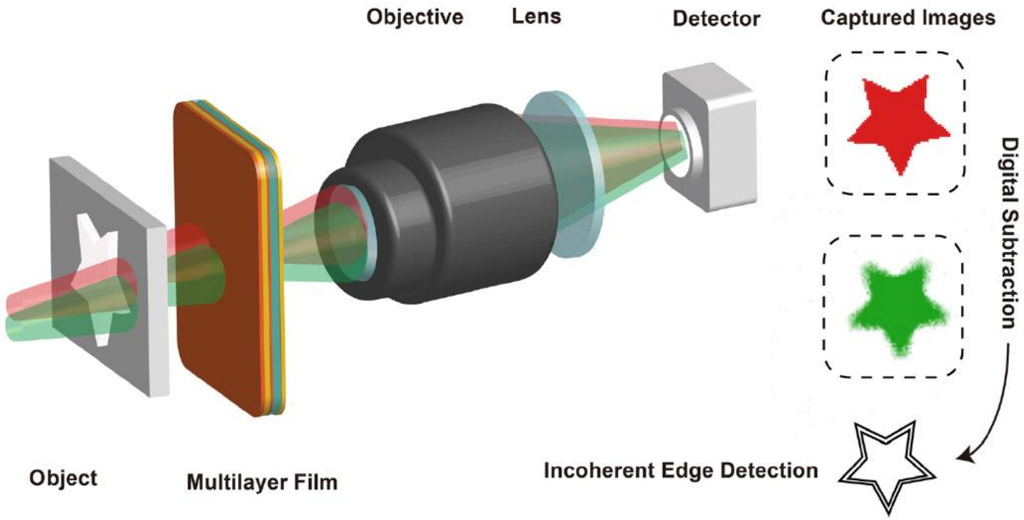
Edge Detection under Incoherent Illumination

Key idea: Process the same image with two different tailored transfer functions (e.g. same metasurface but different wavelengths), and then digitally subtract the two images



Wang et a;, *Compact incoherent image differentiation with nanophotonic structures*. **ACS Photonics**, *7*(2), pp.338-343 (2020).

Shanhui Fan's group



Zhang et al. *Incoherent Optoelectronic Differentiation Based on Optimized Multilayer Films.* **Laser & Photonics Reviews** 16.9 : 2200038 (2022).

Jason Valentine's group

Outline

1. **Introduction**
   - Why do we need analog image processing?
   - How can metamaterials and metasurfaces perform image processing?

2. **Spatial Image Processing: State of the art and Main challenges**
   - What are the different approaches used?
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   - How to overcome the need for coherent illumination?

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   - Spatio-temporal image processing
   - More complex mathematical operations
   - Reconfigurable devices

4. **(Open) Discussion**
   - Beyond the hype: What are (if any) the real benefits of metasurfaces in image processing?
   - Are metasurface-based image-processing devices always worth the effort?

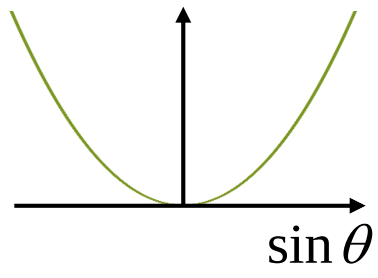
Adding Temporal Processing

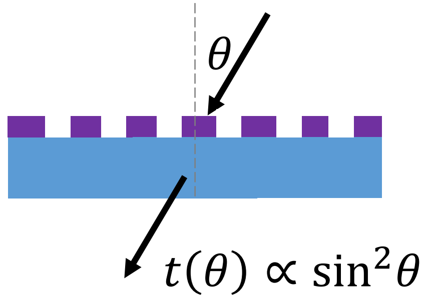
So far we have considered only spatial operations

$$f(x) \rightarrow \frac{\partial^m}{\partial x^m} f(x)$$

$$t(k_x) \propto k_x^m$$

Metasurface's transfer function



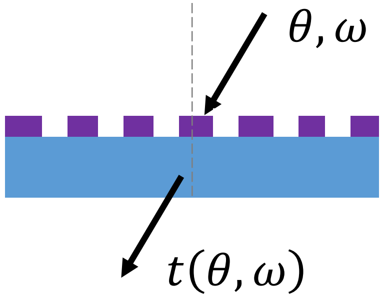


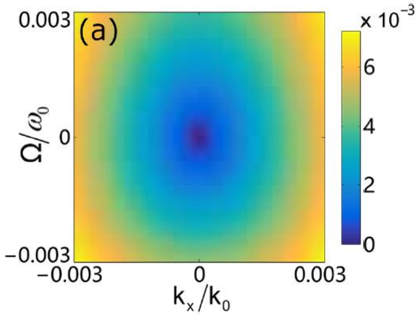
$$f(x,t) \rightarrow \hat{L}_{x,t} f(x,t)$$

$$\hat{L}_{x,t} = C_t \partial_t^m + C_x \partial_x^n$$

$$t(k_x, \omega) \propto C_x k_x^m + C_t \omega^n$$

$$\hat{L}_{x,t} = \begin{cases} \partial_t^m \\ C_t \partial_t^m + C_x \partial_x^n, \\ \vdots \end{cases}$$

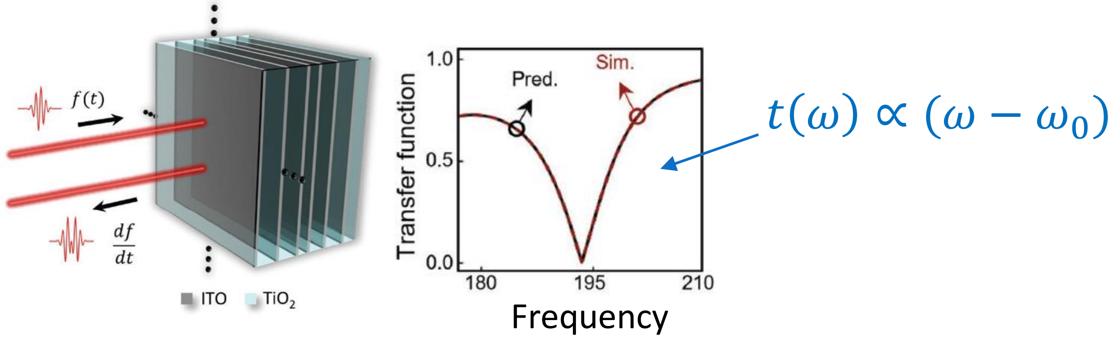




J. Huang et al., **Laser & Photonics Reviews** (2022)

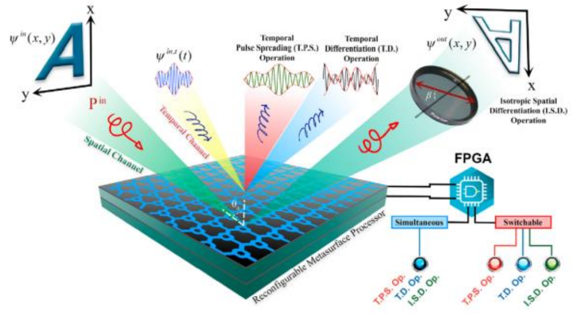
Adding Temporal Processing

Analog Temporal Derivation ∂_t



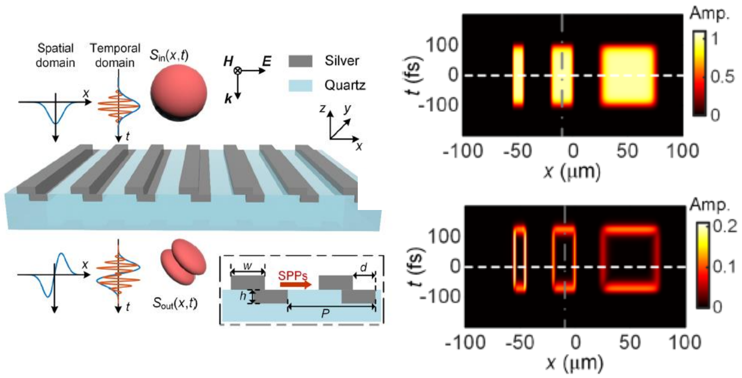
T. Knightley et al., **Advanced Optical Materials** 11.5: 2202351 (2023).

Switching between ∂_t and ∂_x

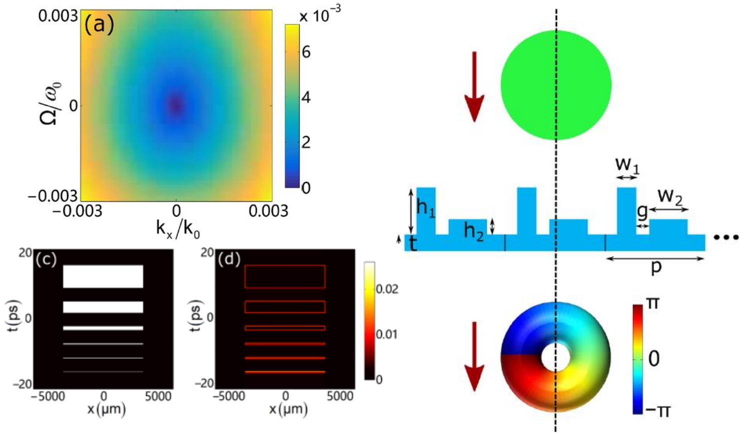


A. Momeni at al., **Carbon**, 186, 599–611 (2022)

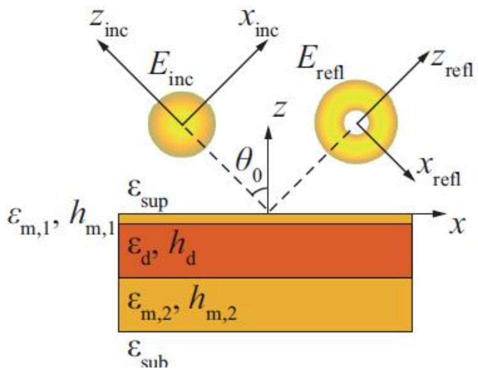
Linear combination: $C_t\partial_t + C_x\partial_x$



C. Xu, et al., **Optics Letters**, 46, 17, 4418–4421 (2021)

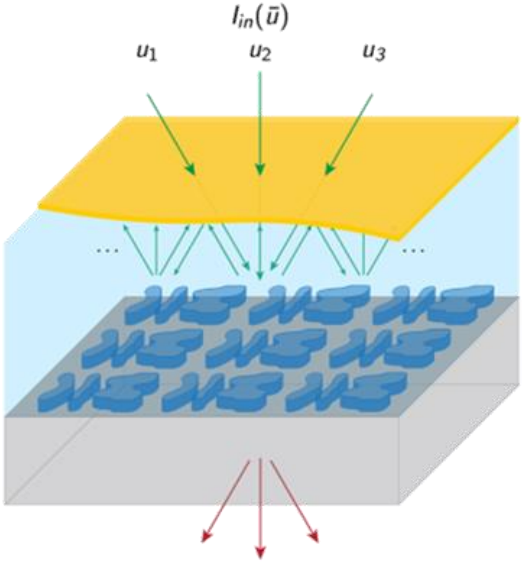


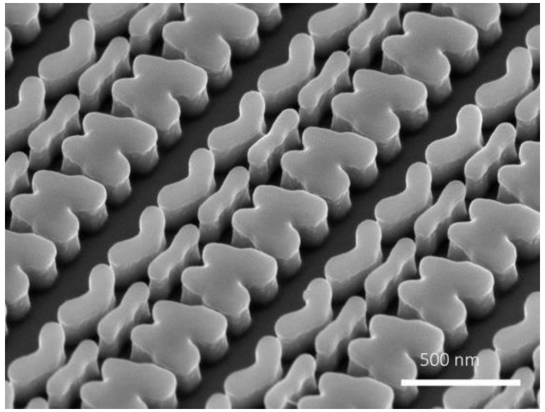
J. Huang et al**., Laser & Photonics Reviews**, 16, 5, p. 2100357 (2022)



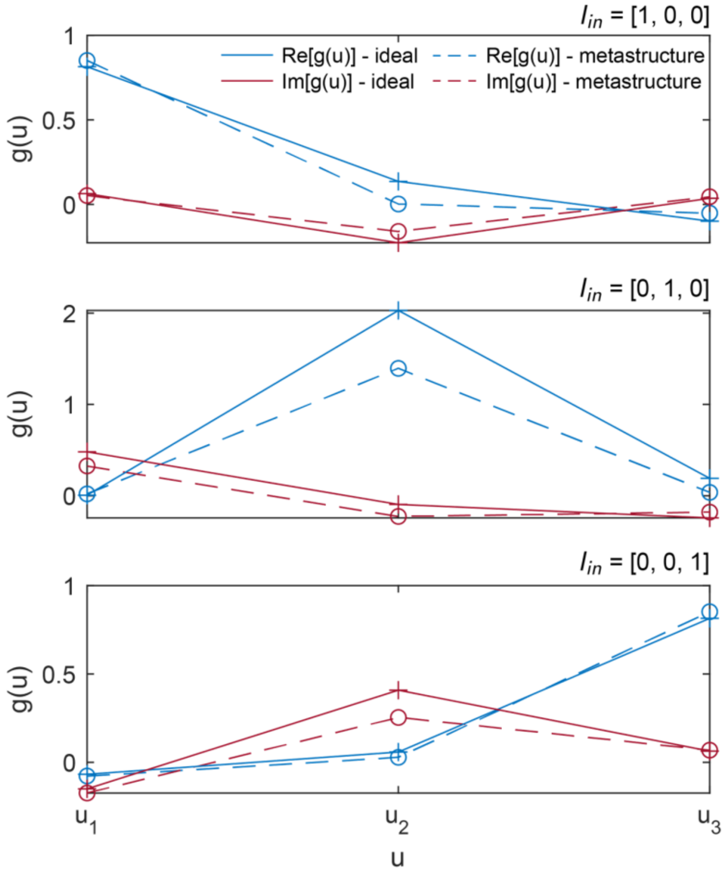
L. L. Doskolovich, et al., **Phys. Rev. A**, 106, 3, 033523 (2022)

More Complex Operations



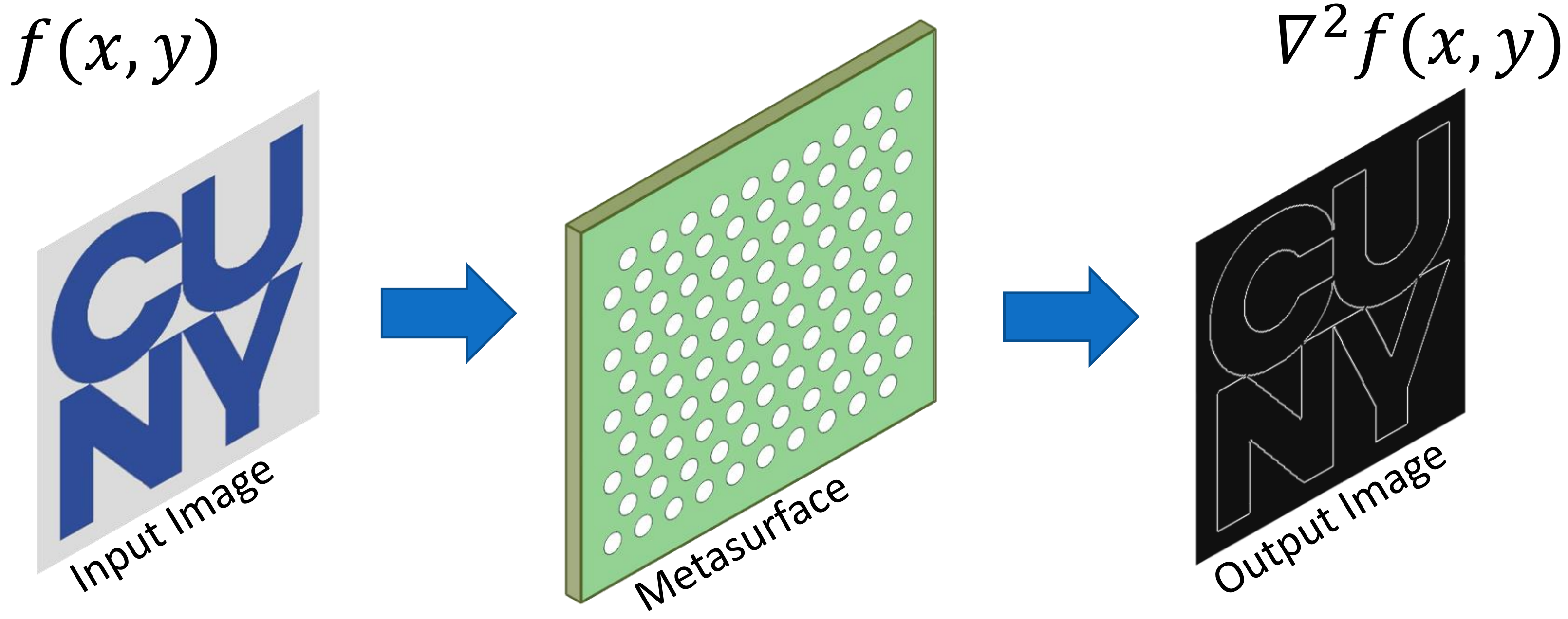


$$g(u) = I_{in}(u) + \int_a^b K(u, v) g(v) dv$$



A. Cordaro, B. Edwards, V. Nikkhah, A. Alù, N. Engheta, A. Polman, *Nature Nanotechnology* (2023)

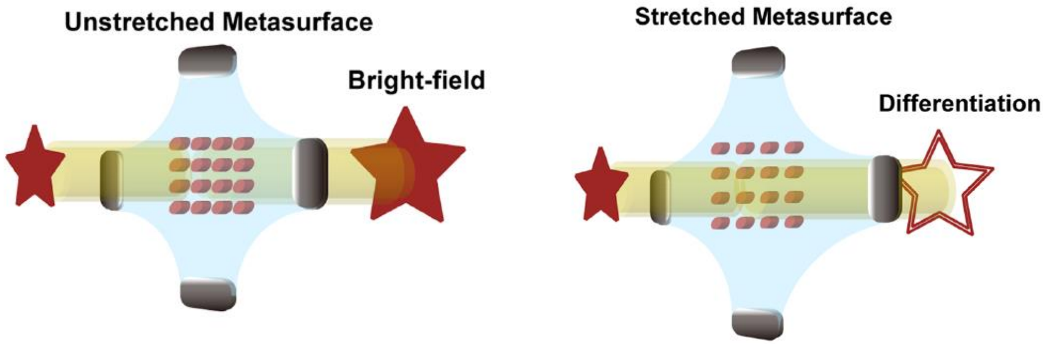
Reconfigurable Metasurfaces



- Most of the devices discussed so far are “static”: once fabricated, they will always perform the same operation
- For practical applications, we need some <u>reconfigurability</u>

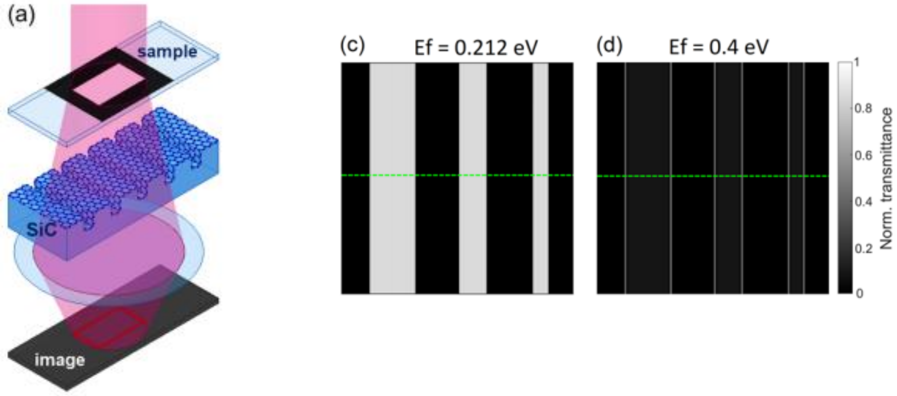
Reconfigurable Metasurfaces

Strain



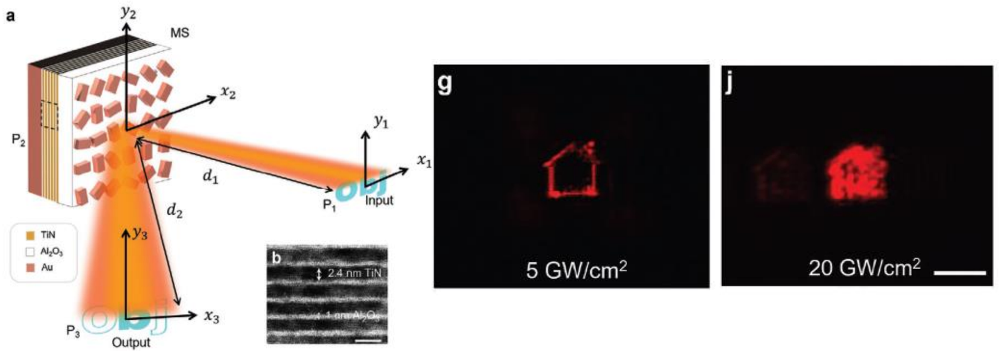
Zhang et al. Nano Letters 21.20: 8715-8722 (2021).

Electrical Tuning

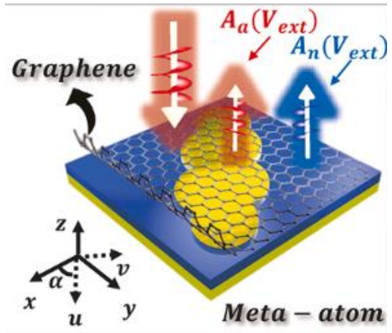


Khodasevych et al. Optical Materials Express 13.5: 1475-1487 (2023).

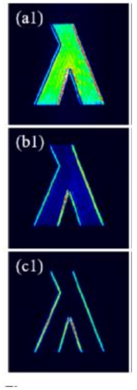
Nonlinear tuning



Zhou et al., Advanced Functional Materials 32.34, 2204734 (2022).



Qiushi, et al., Nanophotonics 11.9: 2085-2096 (2022).



Xiao et al. Optics Letters 47.4: 925-928 (2022)

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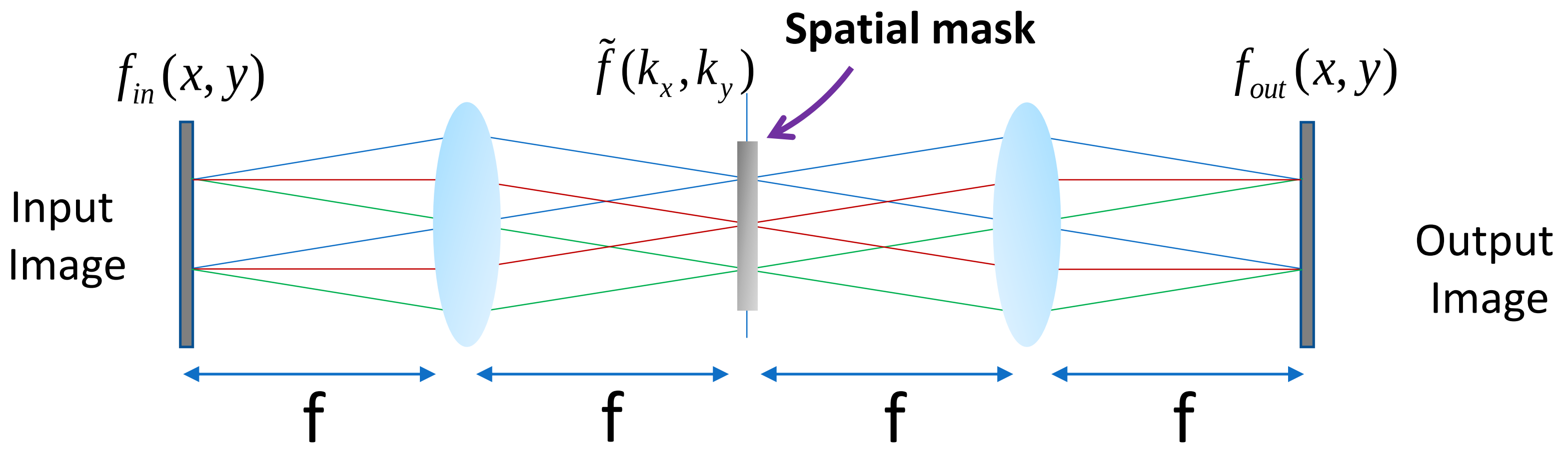
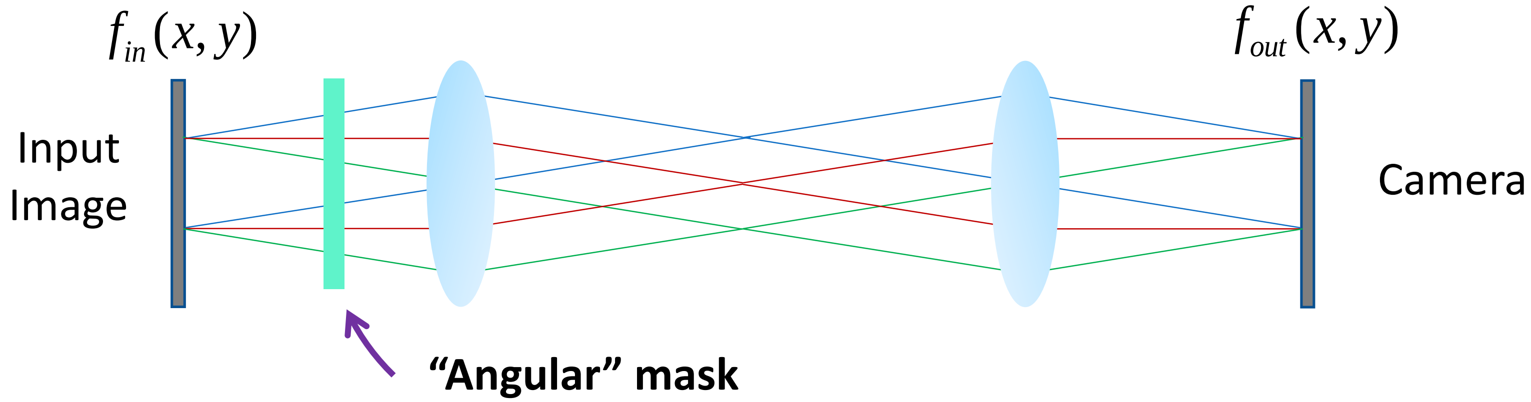
4F or Not 4F? – This is the Question

Standard 4F
k-space filtering



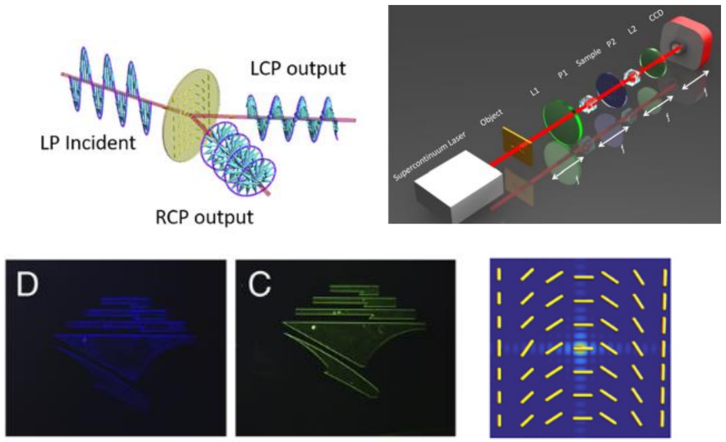
The “metasurface” approach



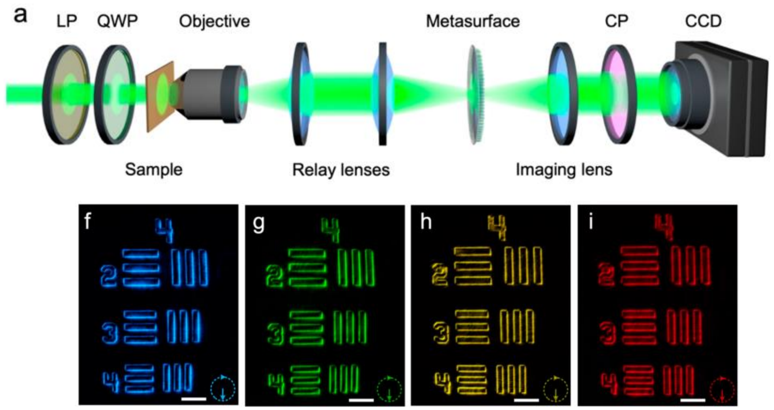
Transfer Function

$$f_{out}(x,y) = \iint dxdy\, t(k_x,k_y)\,\tilde{f}(k_x,k_y)e^{-i(k_x x + k_y y)}$$

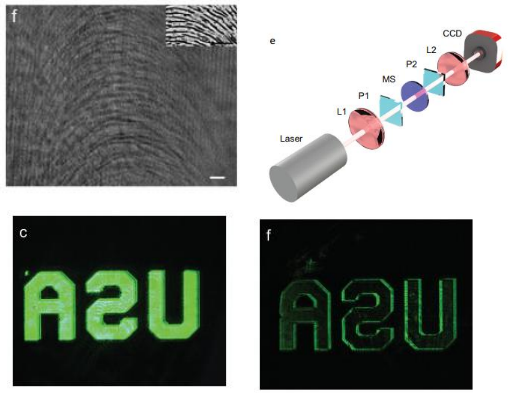
Edge Detection with 4F + Metasurfaces



Junxiao Zhou et al. PNAS 116.23 (2019): 11137-11140.

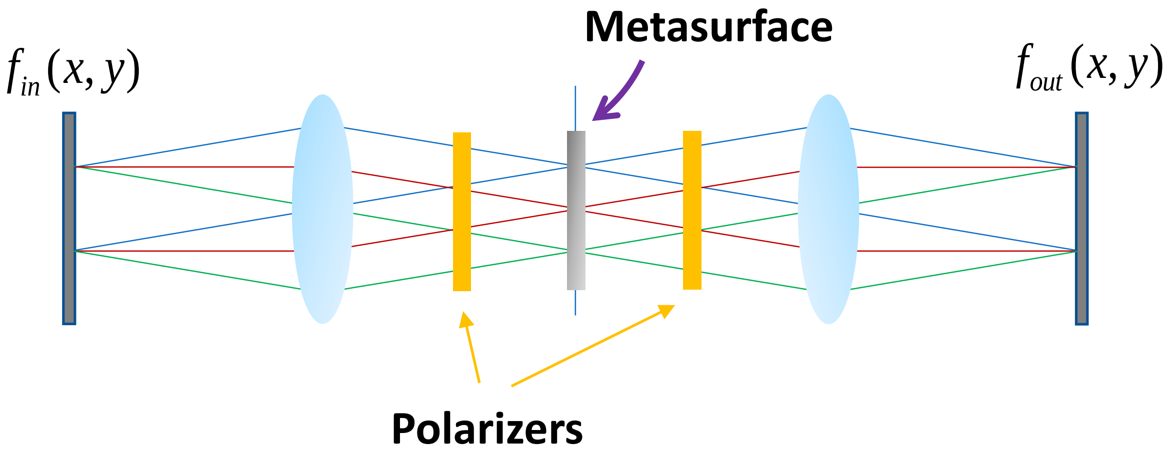


Pengcheng Huo et al., Nano Letters 20.4 (2020): 2791-2798.



Junxiao Zhou et al., National science review 8.6 (2021)

Pancharatnam–Berry-phase metasurfaces + Crossed polarizers



Pros:

- Metasurfaces offer **better control on amplitude and phase** with respect to a binary mask
- **Large bandwidths**, because spectral and angular response are “decoupled”

Cons:

- Require 4F → **cannot be miniaturized**
- Additional requirement of crossed polarizers

OUTLINE

1. Introduction
- Why do we need analog image processing?
- How can metamaterials and metasurfaces perform image processing?

2. Spatial Image Processing: State-of-the-art and Main challenges
- What are the different approaches used?
- Which figures of merit we need to improve to go from proof-of-principles to useful devices?
- How to overcome the need for coherent illumination?

3. What's next?
- Spatio-temporal image processing
- More complex mathematical operations
- Reconfigurable devices

4. (Open) Discussion
- Beyond the hype: What are (if any) the real benefits of metasurfaces in image processing?
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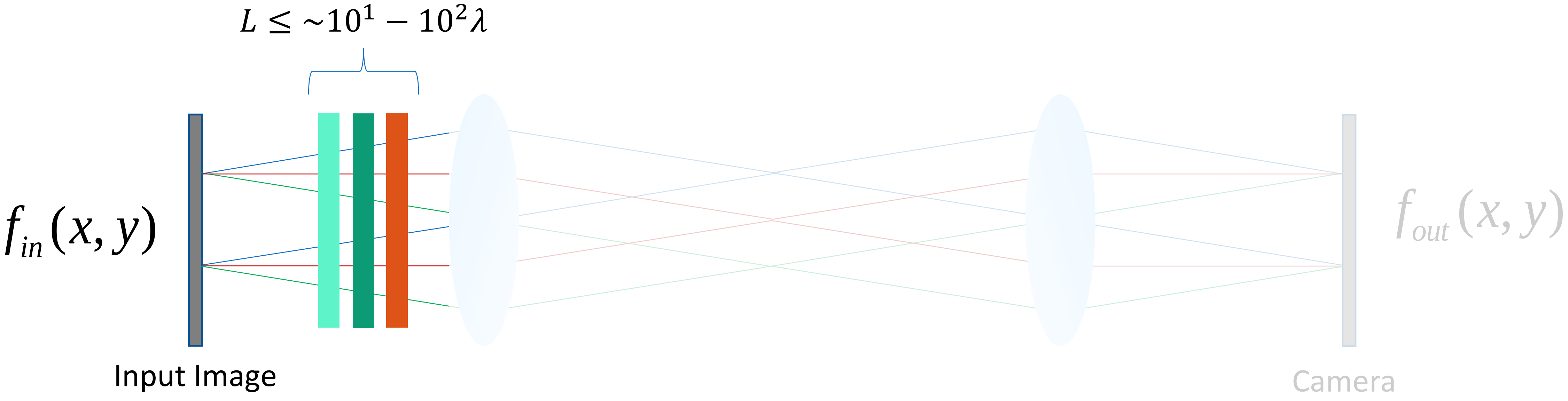
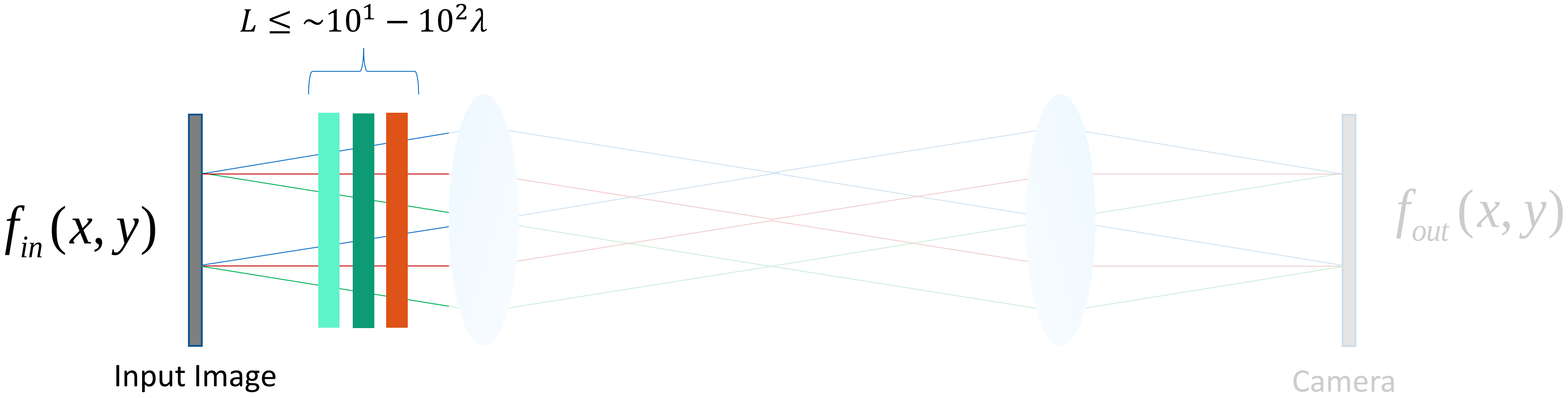
BEYOND THE HYPE



- **Compactness** → No need for a 4F system (in principle)
- **Scalability** → Multiple operations could be cascaded, without the need of additional optics
- **More tolerance on spatial alignment**
- …. More?

Beyond the Hype



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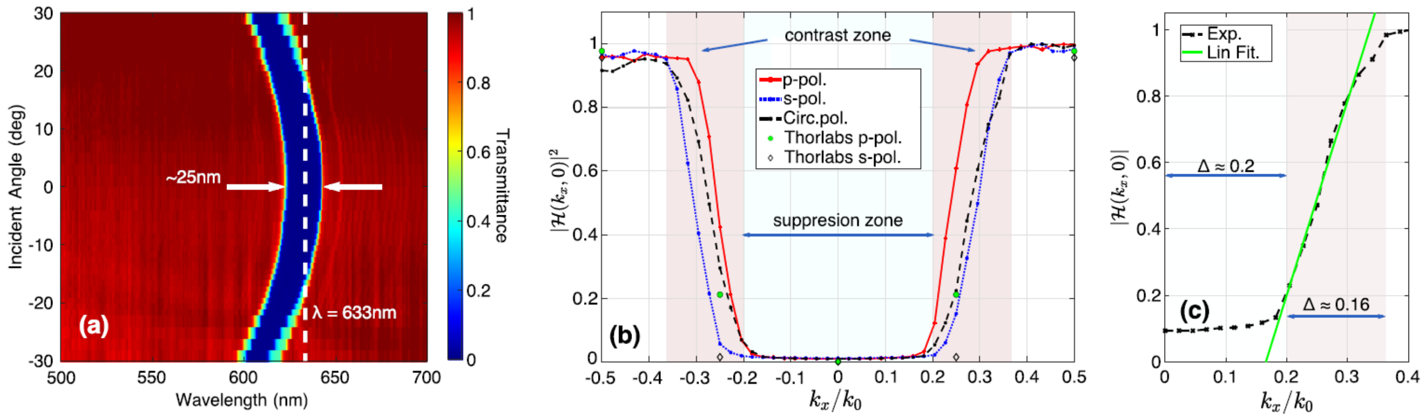
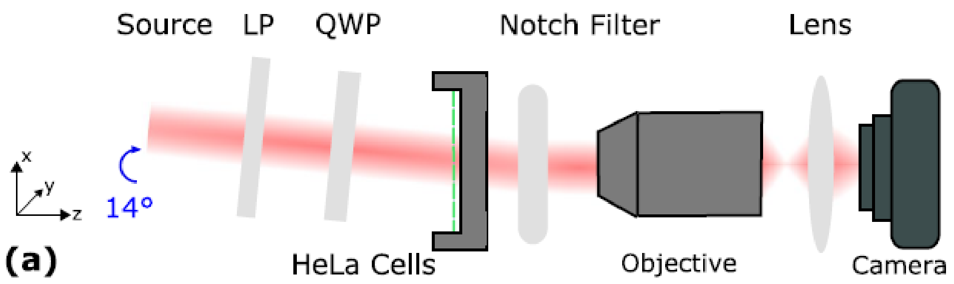
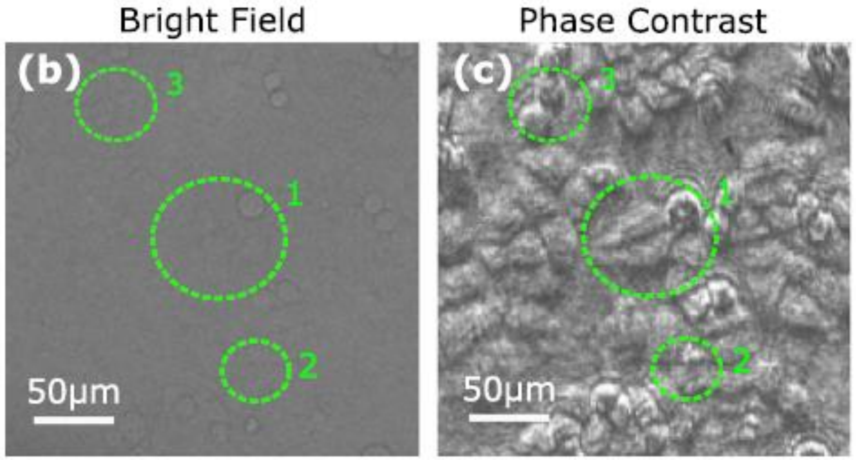
Bulkier Approaches

Are metasurface-based image-processing devices always worth the effort?

Commercially-available
Notch Filter

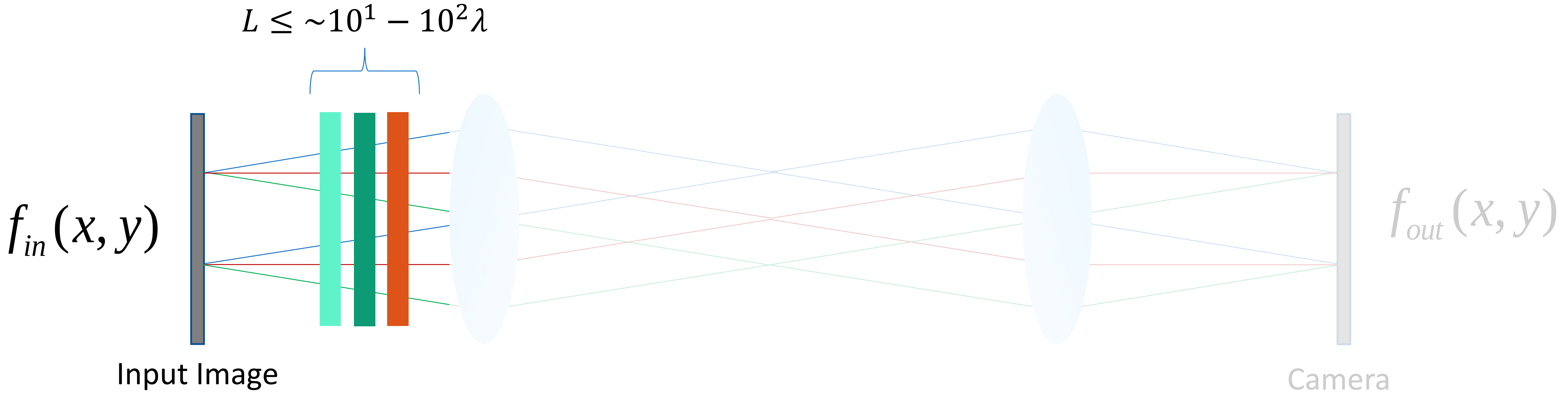






Sulejman et al., *Thin film notch filters as platforms for biological image processing*. **Scientific Reports**, 13(1), p.4494 (2023)

Beyond the Hype



- **Compactness**
- **Scalability**
- **More tolerance on spatial alignment**

No free lunch in the universe:

- Many trade-offs between crucial figures of merit
- (so far) Limited set of operations demonstrated
- Limited reconfigurability

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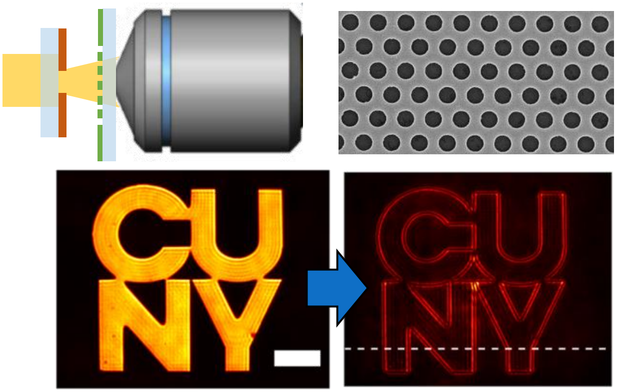

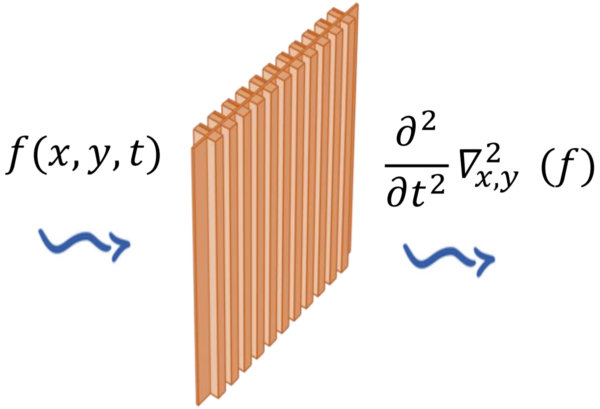

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