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Item title: Implosion Fabrication as a Platform
for Three-Dimensional Nanophotonics

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Massachusetts Institute of Technology

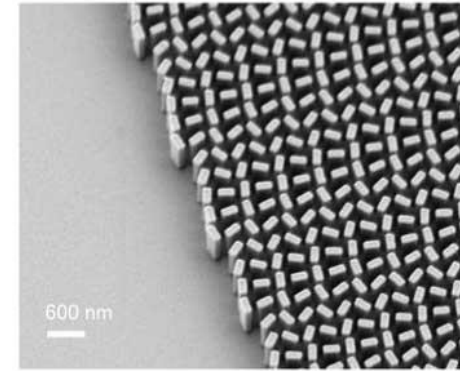
Implosion Fabrication as a Platform for Three-Dimensional Nanophotonics

Brian Mills, Yannick Salamin, Gaojie Yang, Daniel Oran, Yi Sun,
Shai Maayani, Steven E. Kooi, Amel Amin Elfadil Elawad, Josue J.
Lopez, Corban Swain, Justin Beroz, Jamison Sloan, Edward S.
Boyden, Marin Soljacic

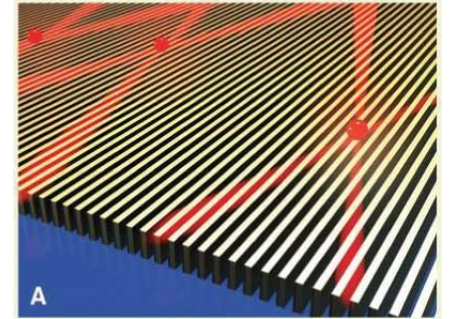


Nanophotonics

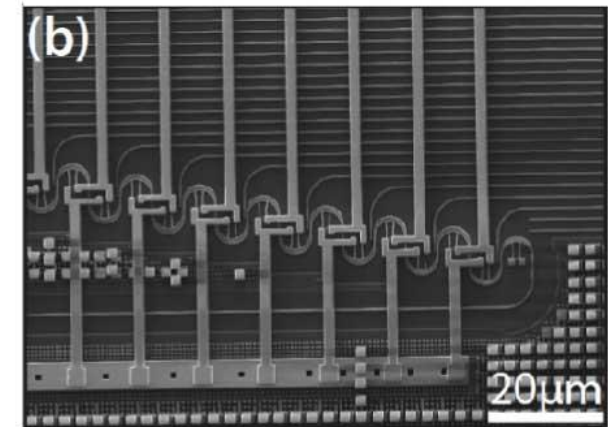
- Nanophotonics – manipulation of light at nanometer length scale.
 - UV – NIR optical devices
 - Optical metamaterials
 - Integrated photonic circuits
- Current technology relies on high resolution 2-dimensional lithography.
- 3D nanophotonic structures realize full potential for photonic devices



Khorasaninejad et al. *Science* 358.6367 (2017).



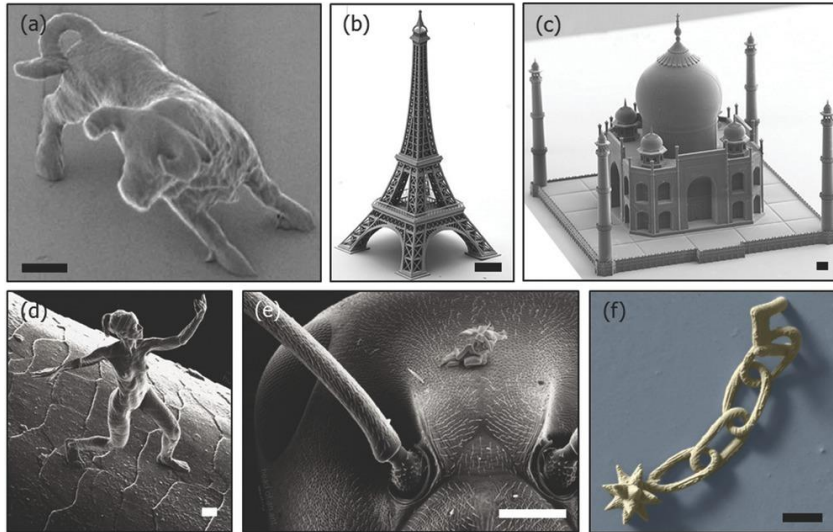
Kildishev et al. *Science* 339.6125 (2013).



Poulton et al. *Optics letters* 42.20 (2017): 4091-4094.

3D Nanofabrication

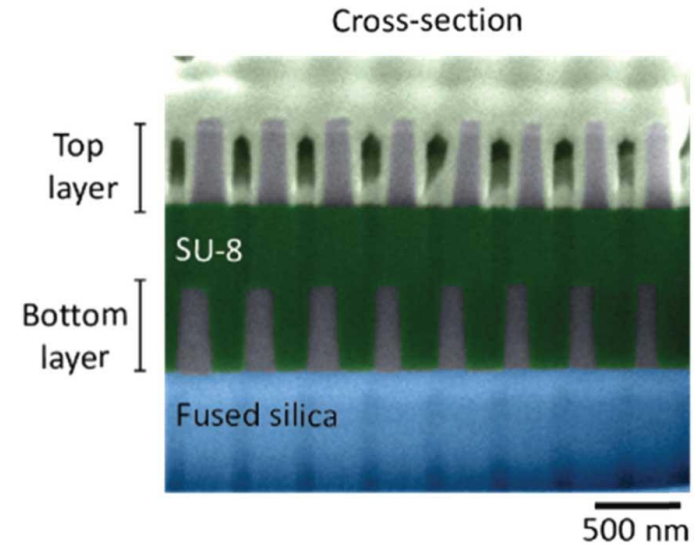
Polymer Two Photon Lithography



Yetisen et al Advanced Materials 28.9 (2016): 1724-1742.

- High resolution free-form geometries.
- No choice of material.
 - Polymer has low index contrast.
- All structures must be interconnected.

Layer Deposition “2.5D structures”



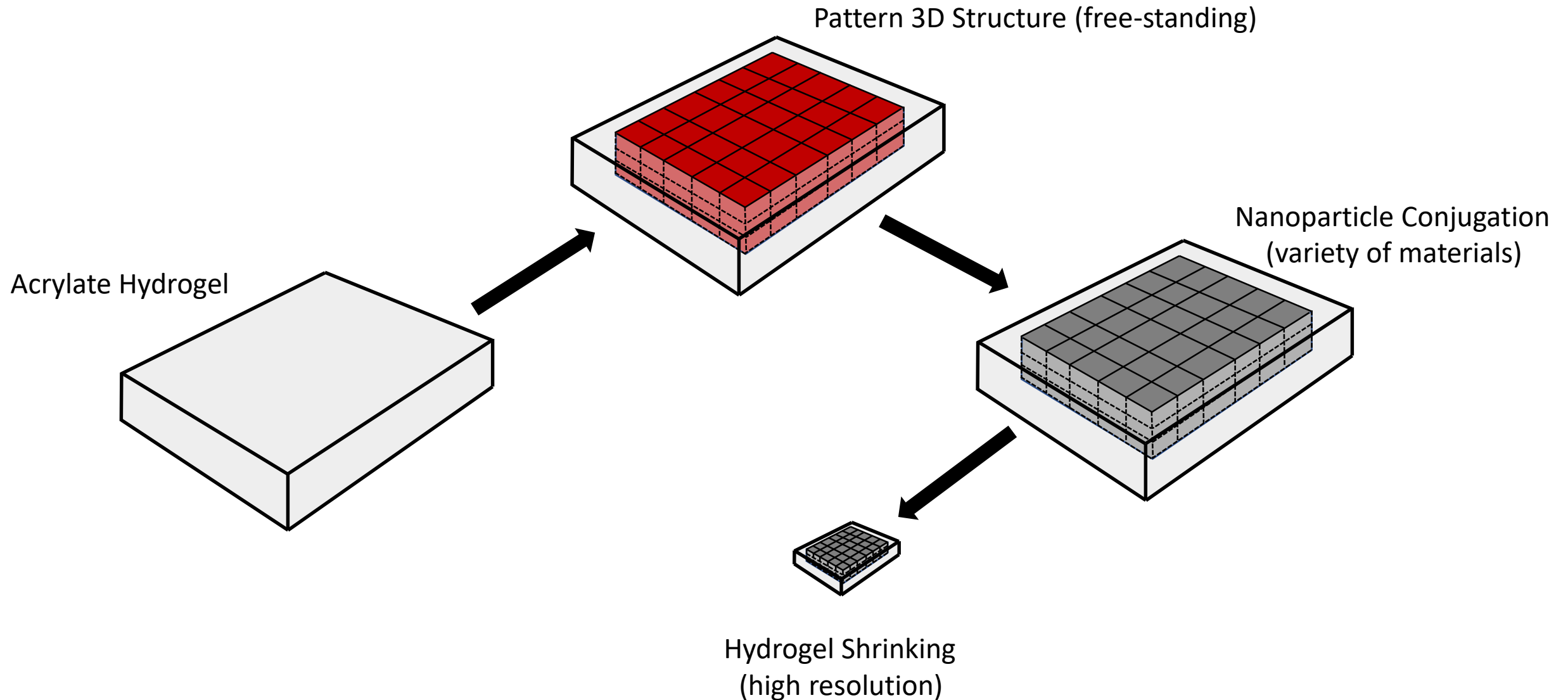
Mansouree et al, Optica 7.1 (2020): 77-84.

- High in-plane resolution.
- Heavily restricted in geometry.
- Sensitive to layer alignment.

An Ideal 3D Nanofabrication Platform

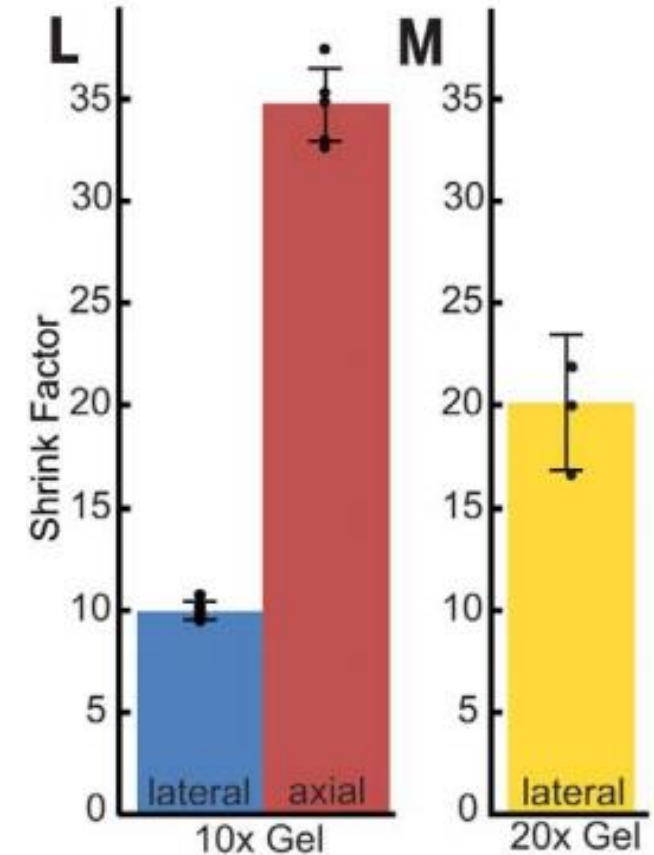
- High resolution in all 3 spatial dimensions.
- Freestanding structures.
- Easily integrate multiple materials.
- Continuously varying material density (control permittivity $\epsilon(x, y, z)$).

Implosion Fabrication



Acrylate Hydrogel

- Gel synthesized using sodium acrylate, acrylamide and bis-acrylamide.
 - Exhibit large volumetric shrinkage after dehydration.
- Shrink factor of gel controlled with concentration of bis-acrylamide.

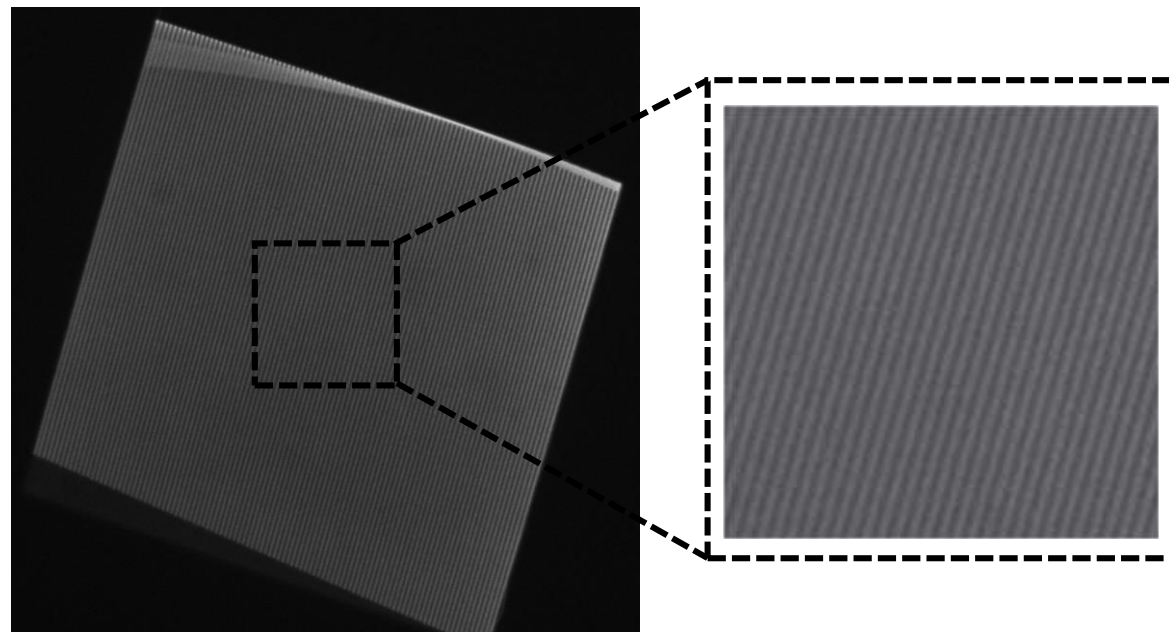
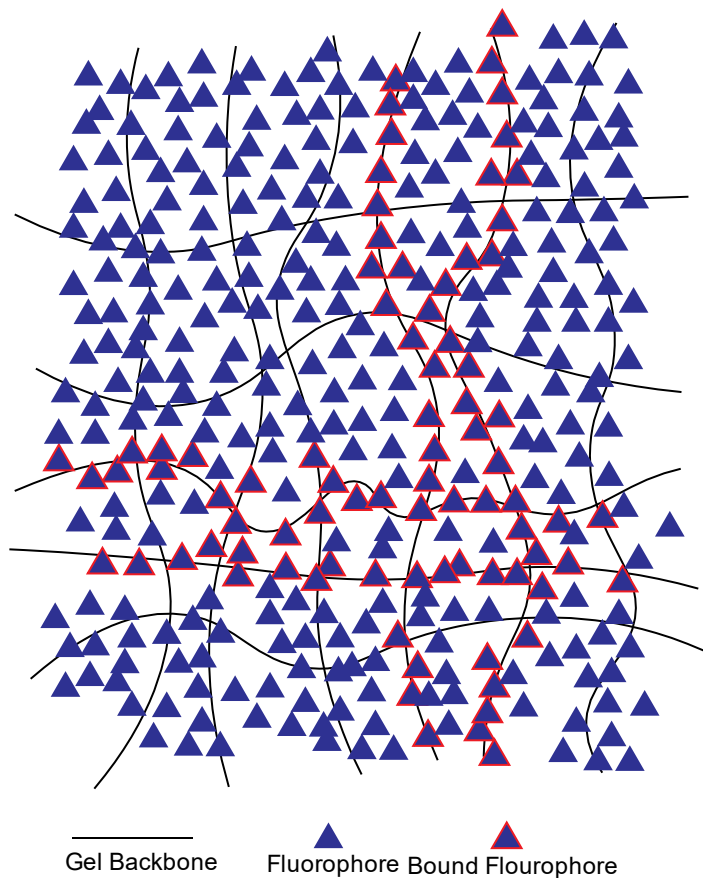


Oran, et. al *Science* 362.6420 (2018): 1281-1285

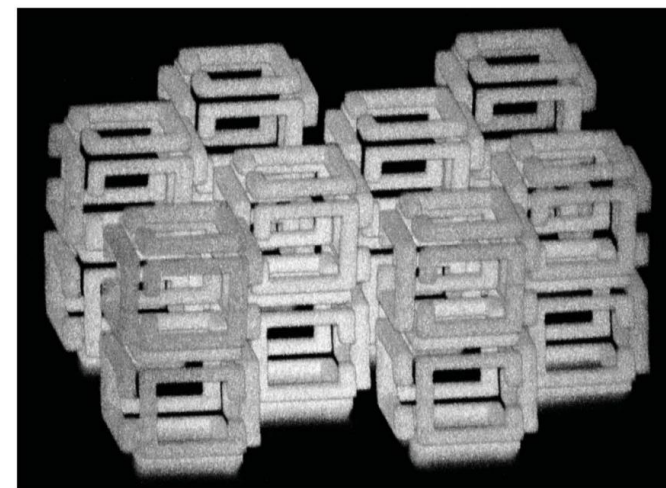
Patterning of Hydrogels



Patterning



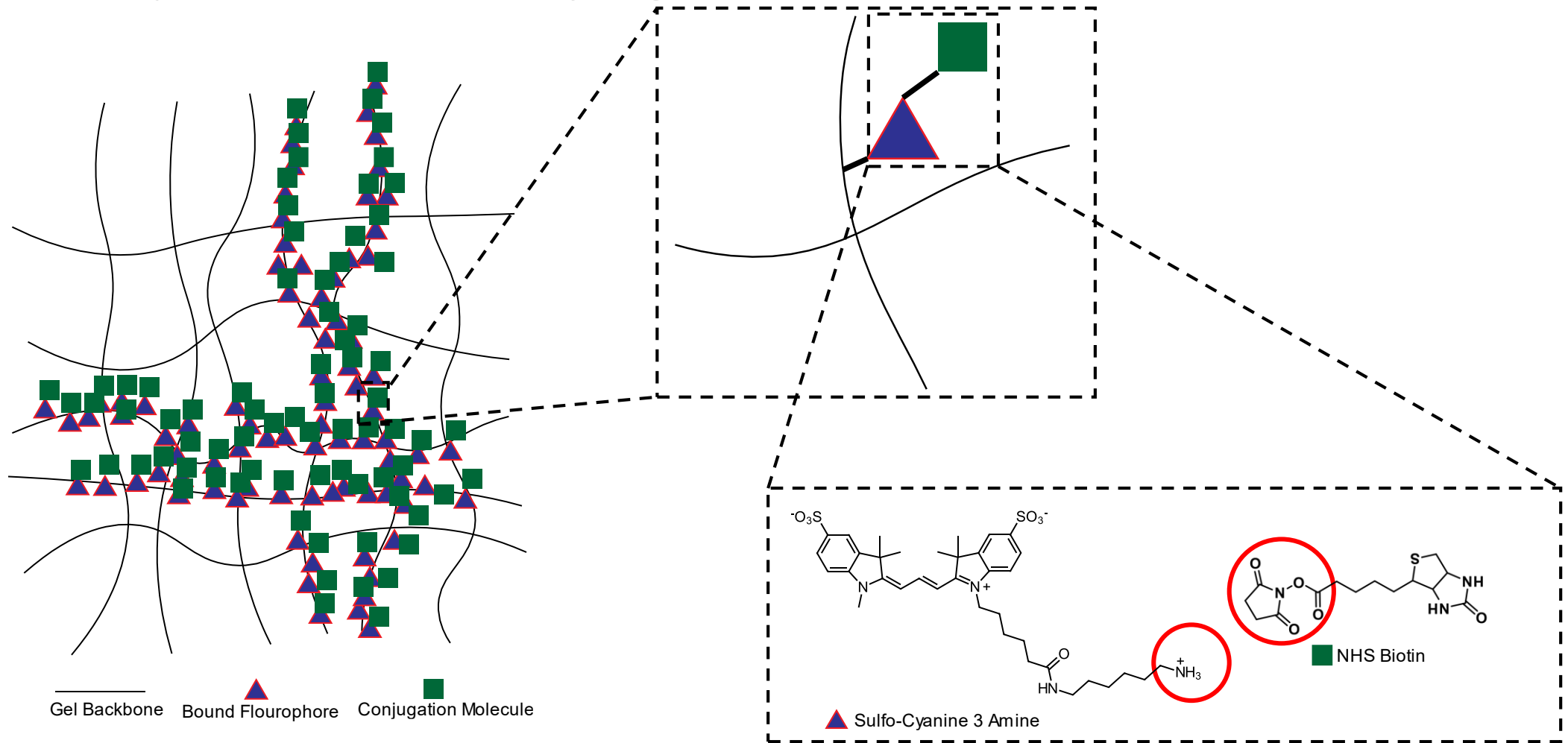
100 μm



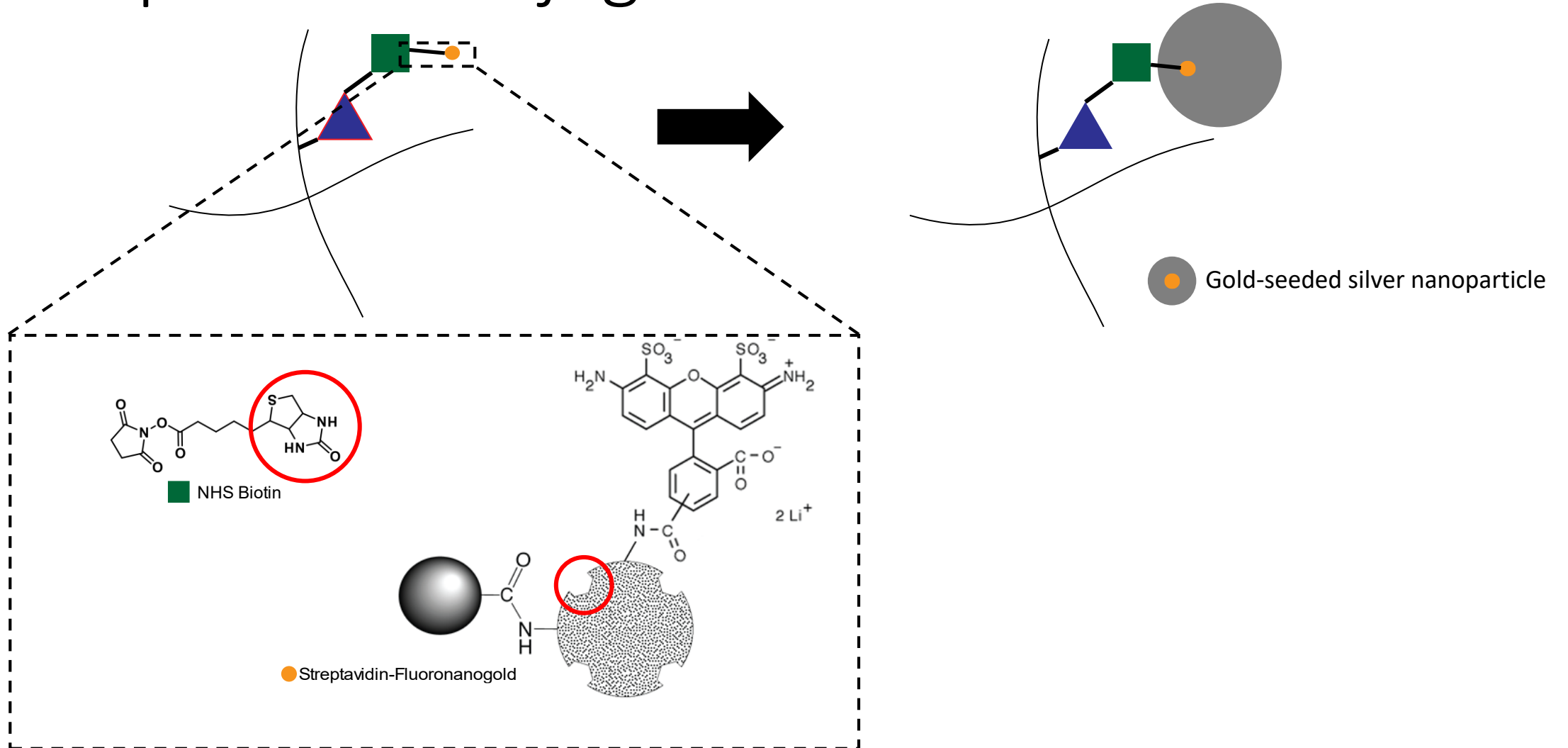
100 μm

Oran, et. al *Science* 362.6420 (2018): 1281-1285

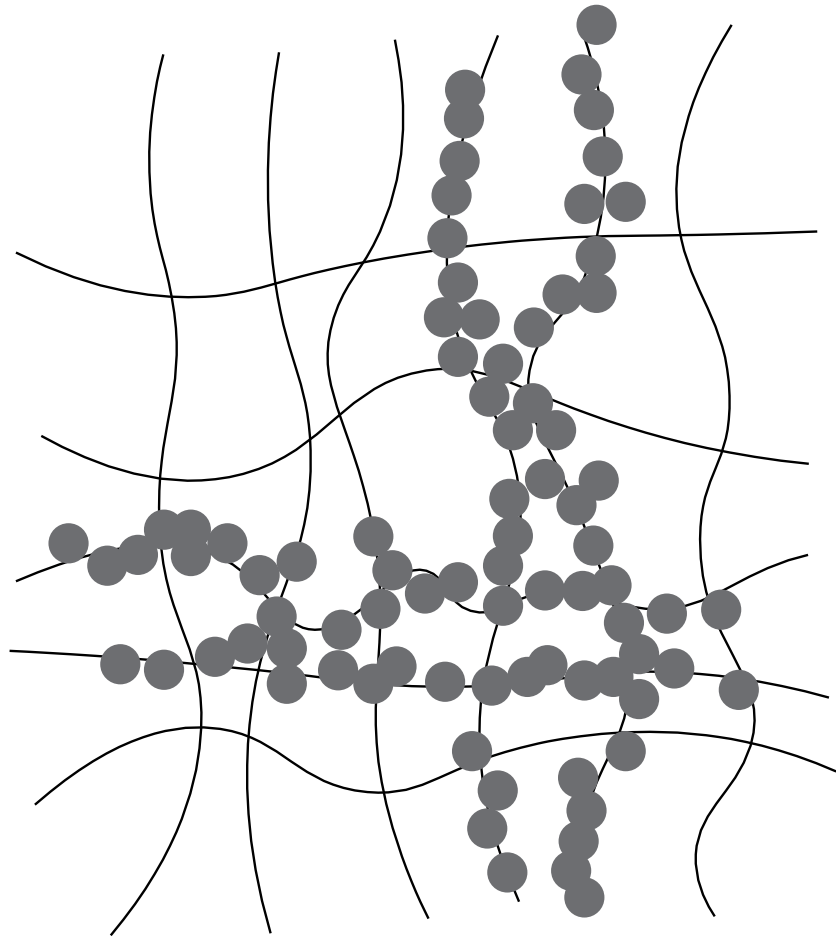
Nanoparticle Conjugation



Nanoparticle Conjugation



Gel Dehydration

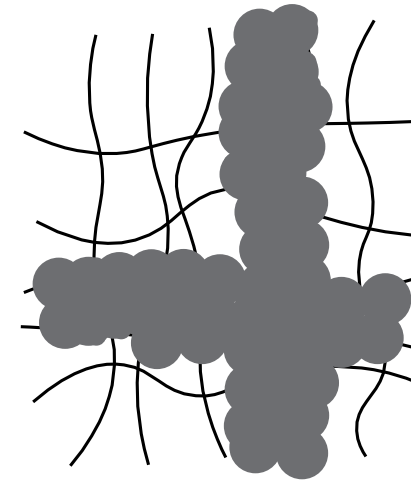


— Gel Backbone
● Silver Nanoparticle

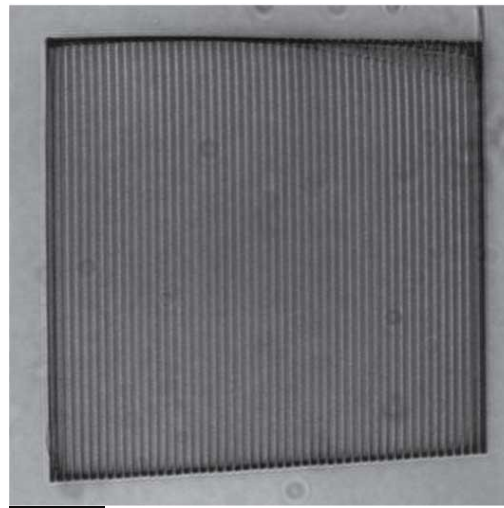
Wash in salt solutions



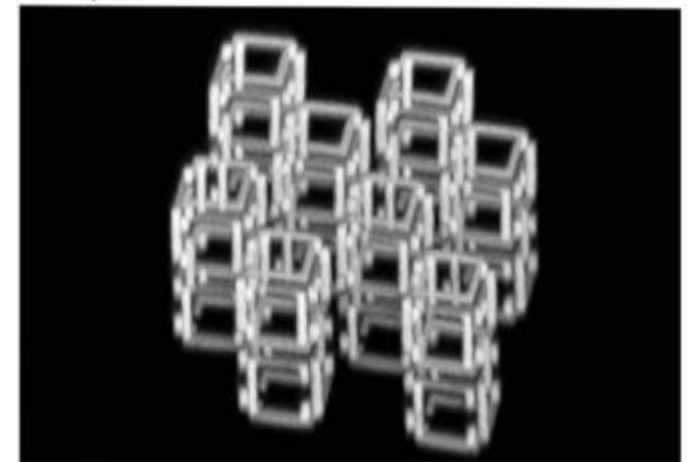
Gel shrinks 10-20x



— Gel Backbone
● Silver Nanoparticle



10 μm



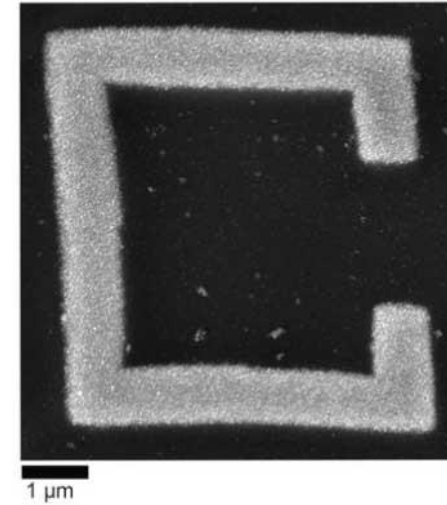
10 μm

Oran, et. al *Science* 362.6420 (2018): 1281-1285

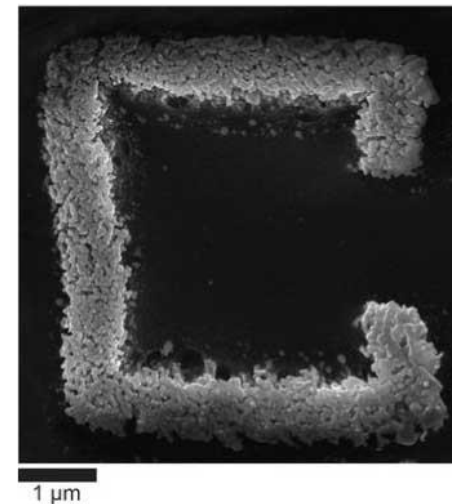
Sintering (Optional)

- Focus laser onto sample.
 - Local heating avoids gel degradation.
- Fuses silver particles together.
- Improves silver conductivity.

Before

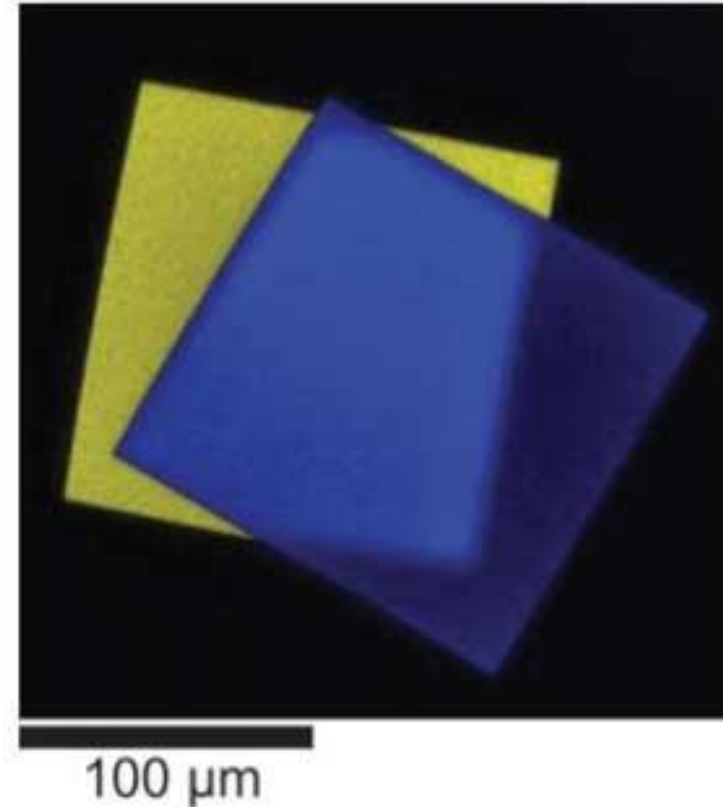


After



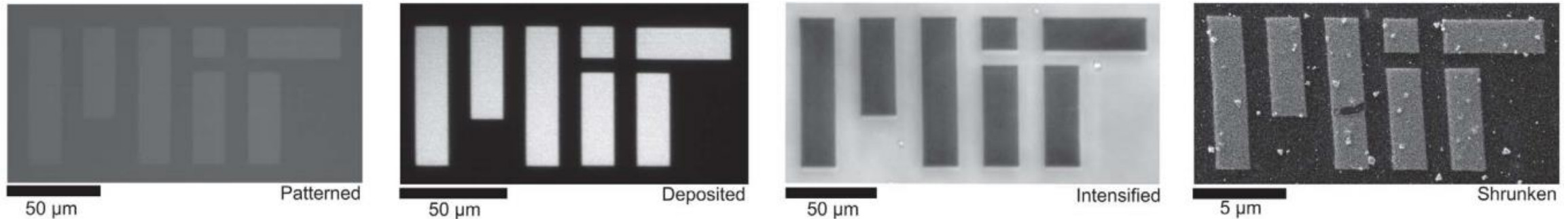
Patterning Multiple Materials

- Sequentially pattern using different fluorophores.
- Use different conjugation chemistry for each material.



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Implosion Fabrication Overview

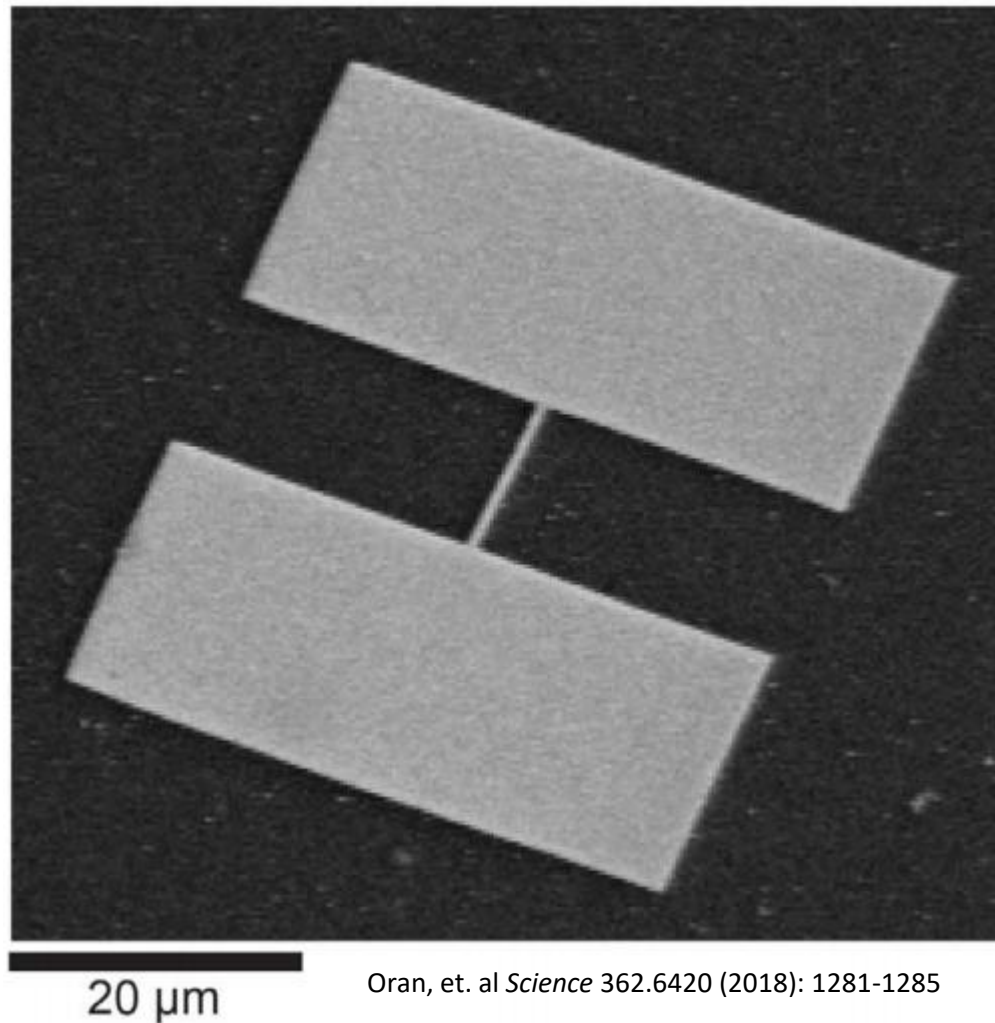


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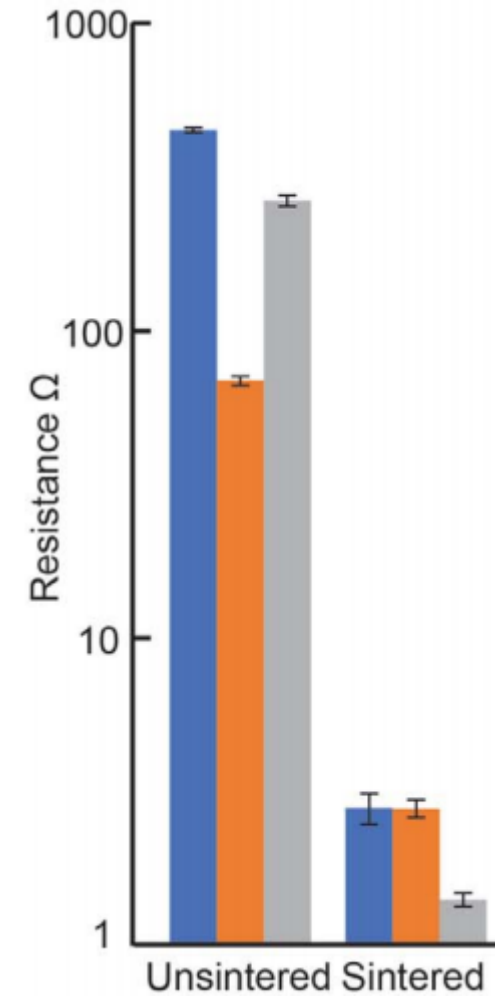
Advantages of Implosion Fabrication:

- Low resolution patterning -> High resolution structures.
- Free standing structures.
- Potential multi-material structures.

Characterization of Implosion Fabrication Silver

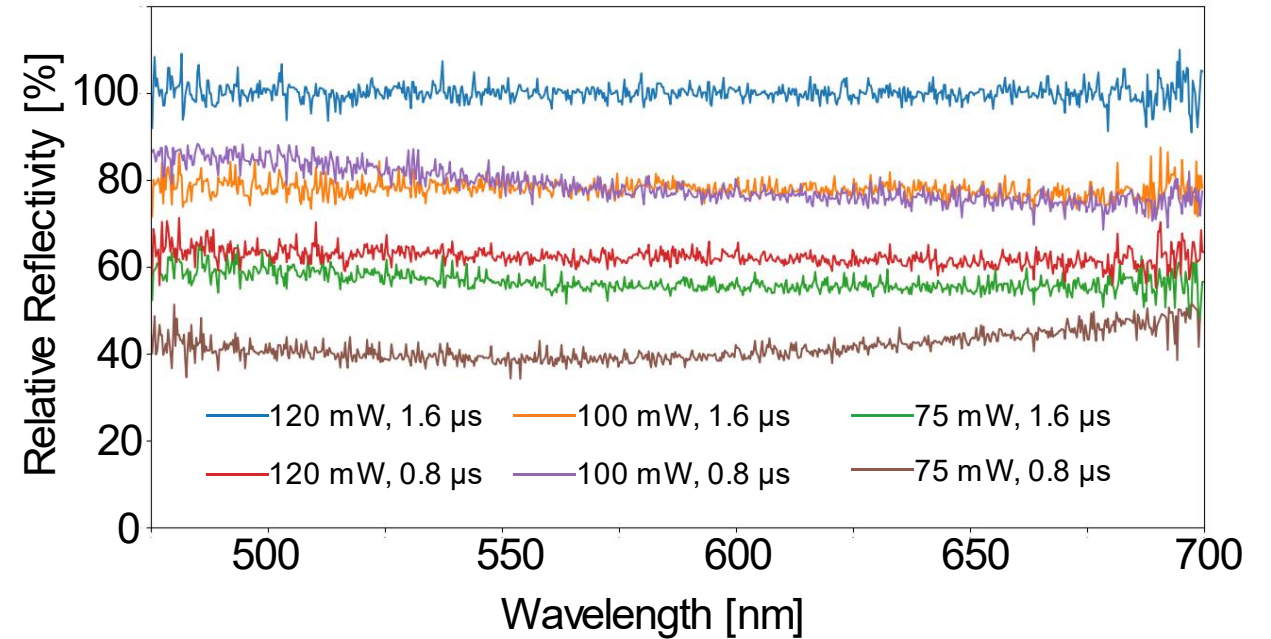
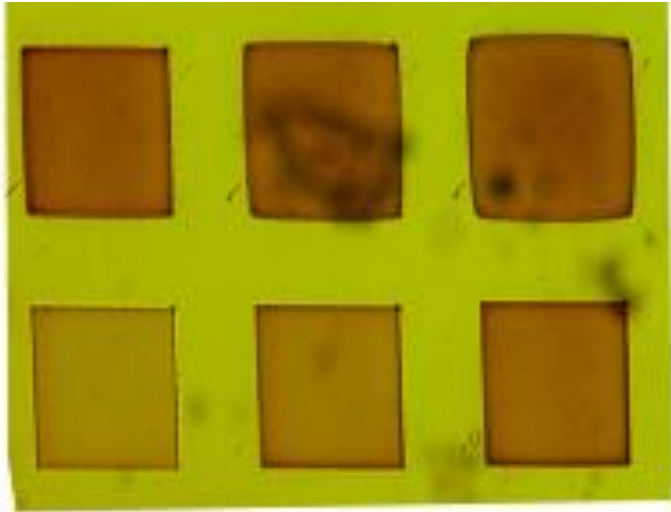


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Optical Characterization of Deposited Silver



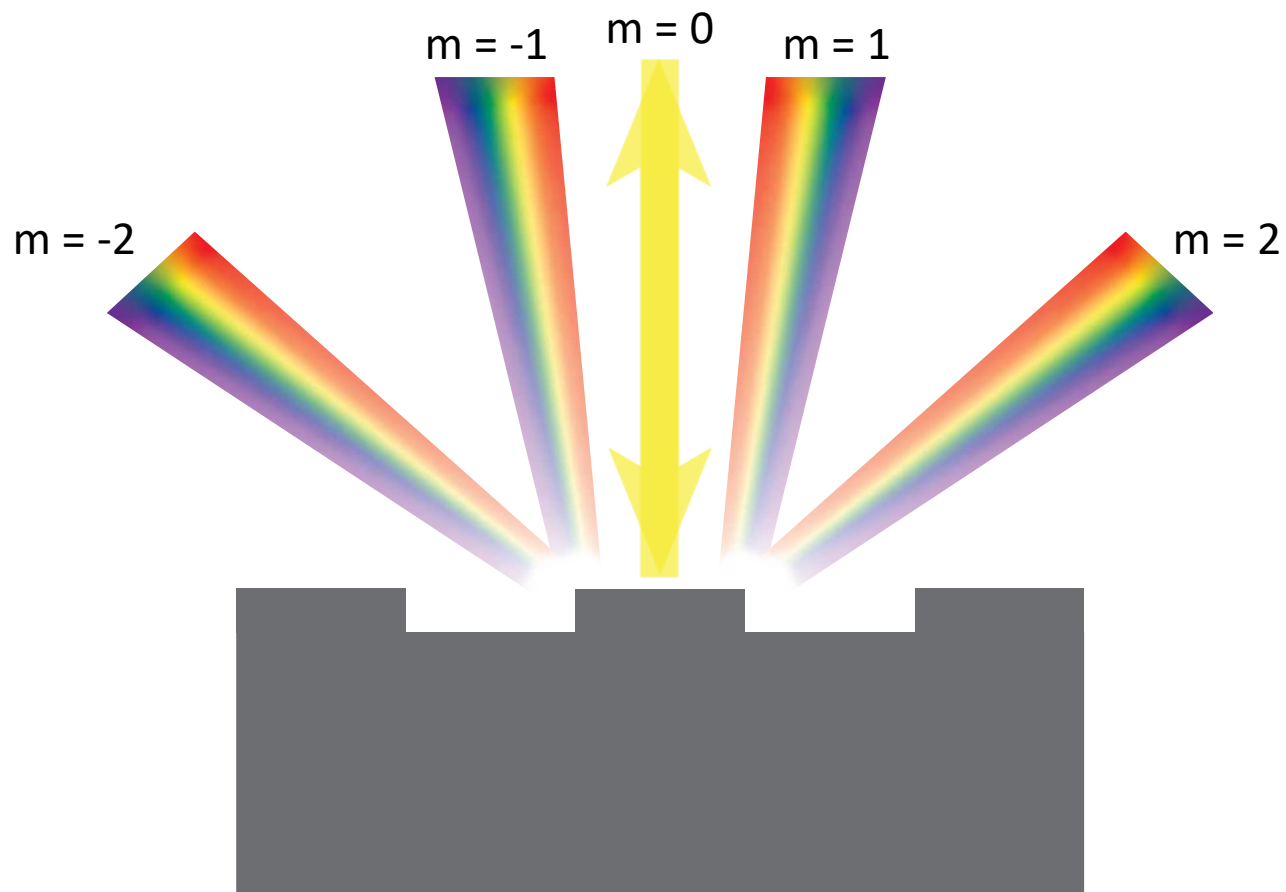
Reflective Diffraction Grating

θ_m – diffraction angle λ – wavelength

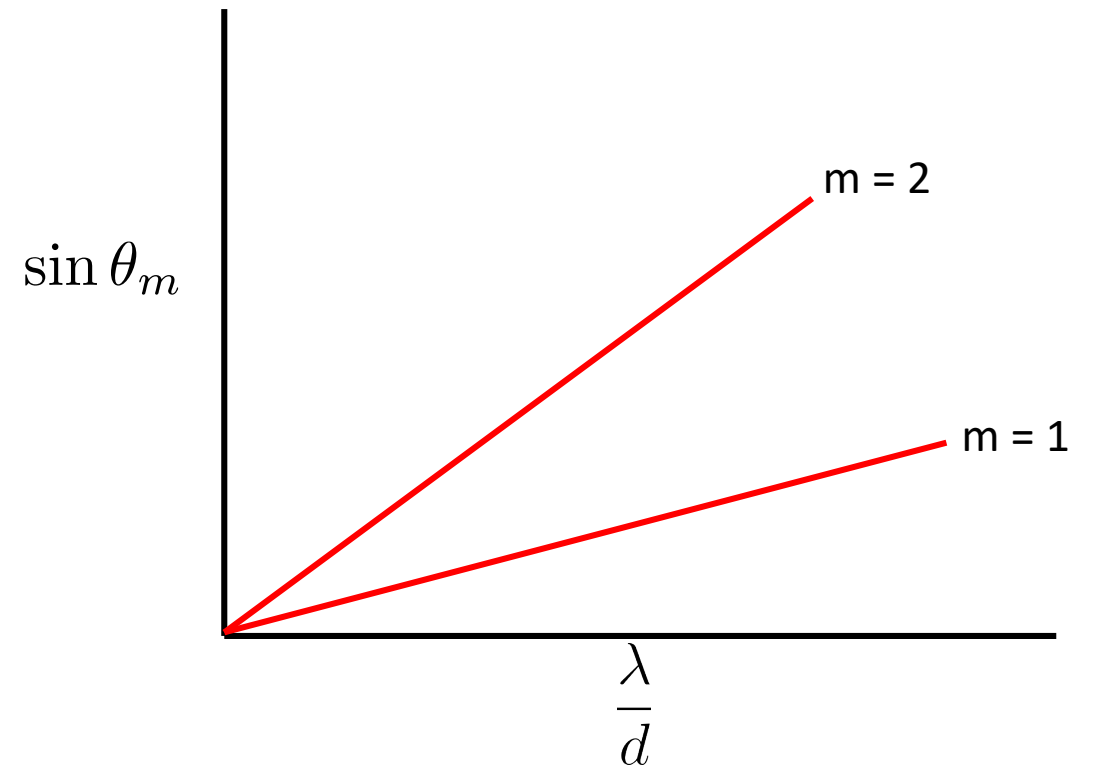
θ_i – angle of incidence d – grating period

m – diffraction order

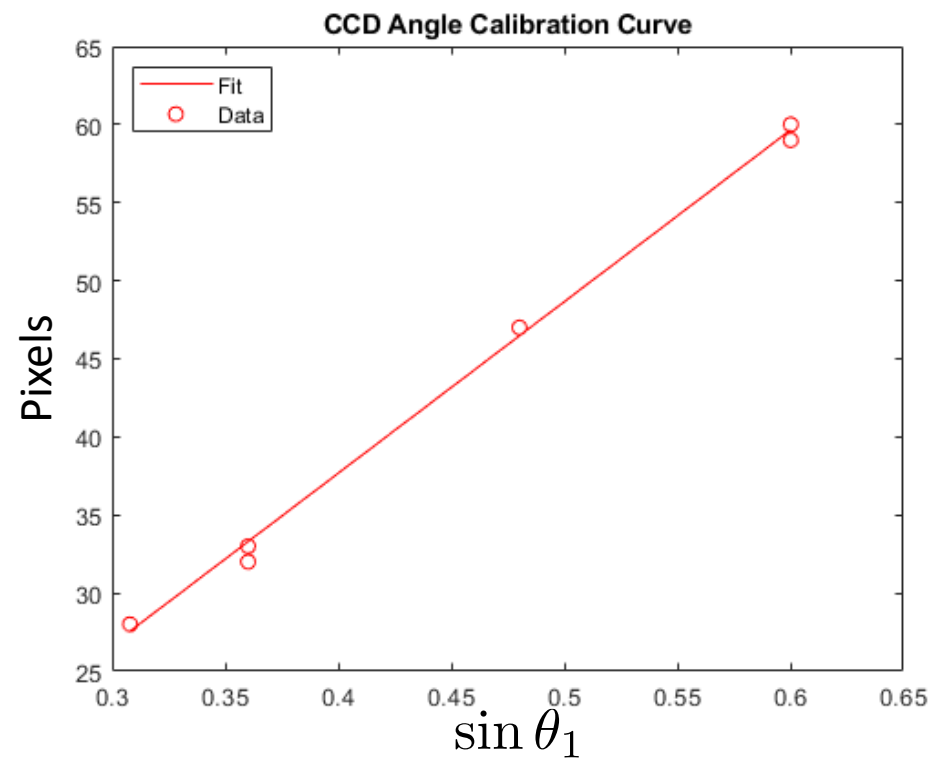
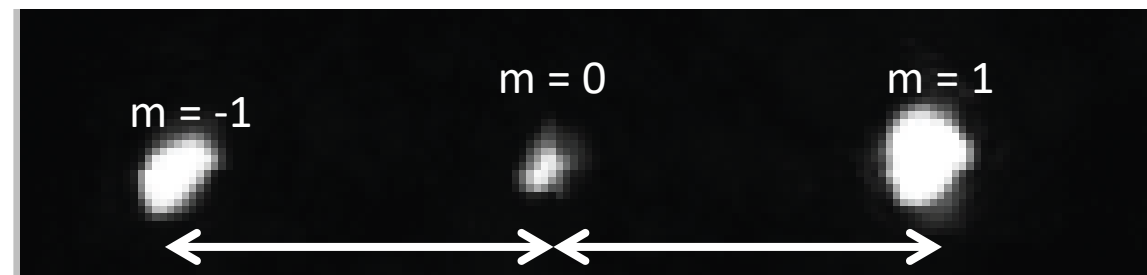
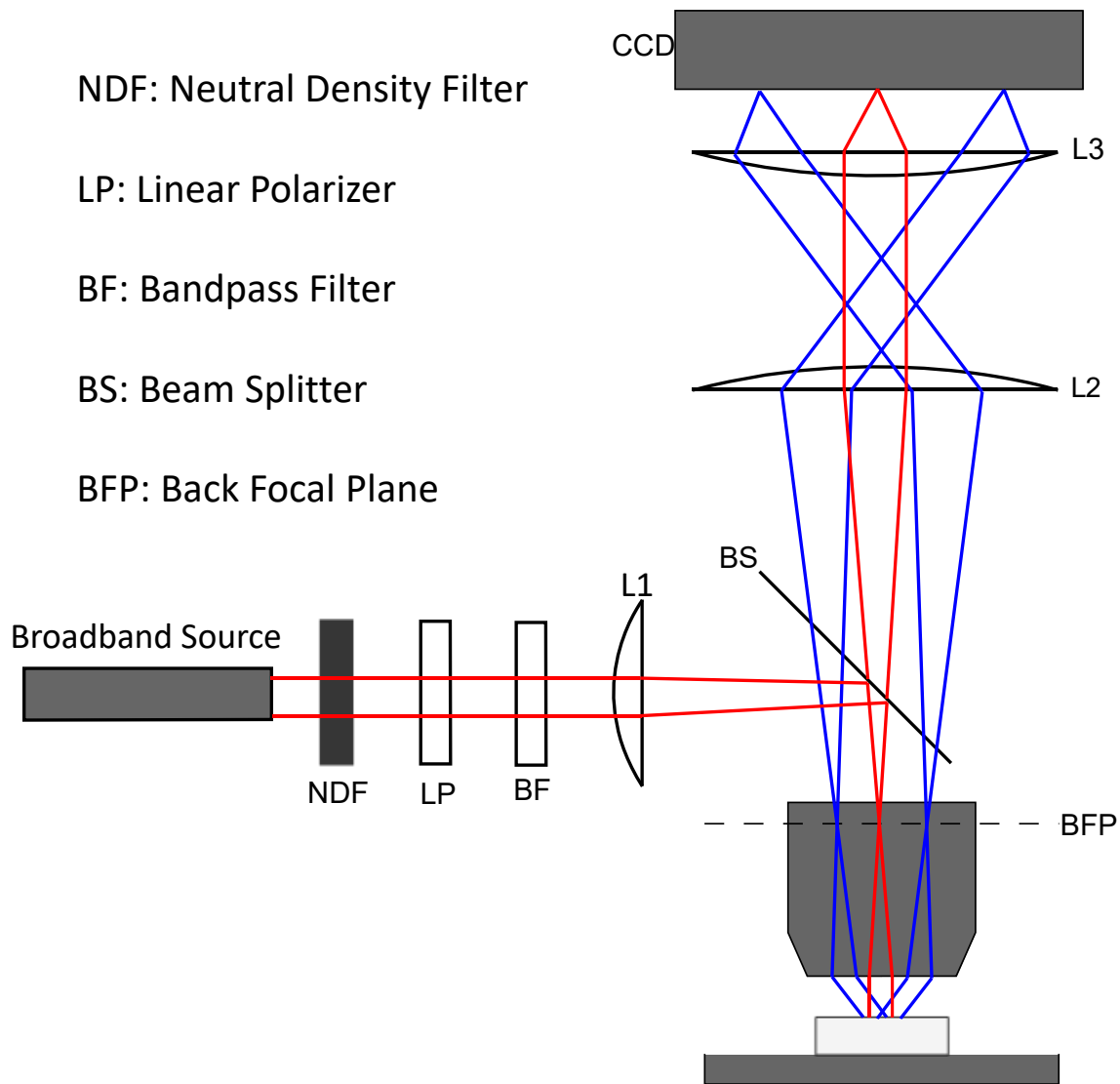
n – medium refractive index



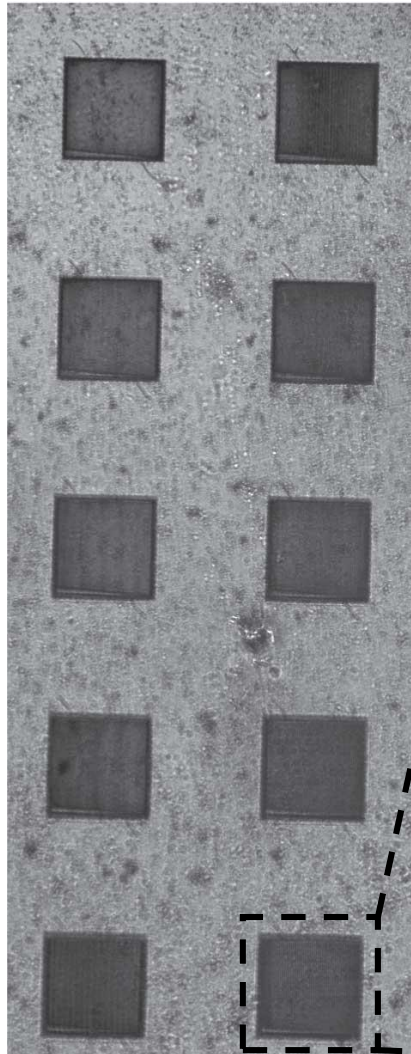
$$\sin \theta_m + \sin \theta_i = \frac{m\lambda}{nd}$$



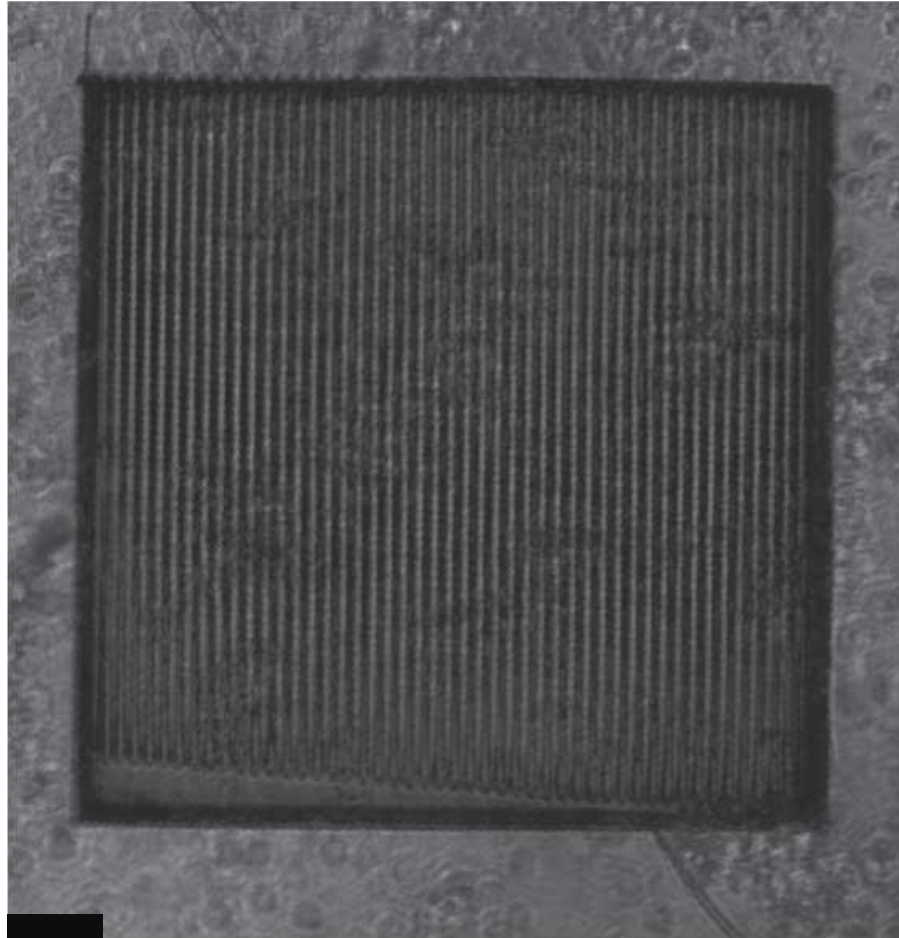
Fourier Microscopy Setup



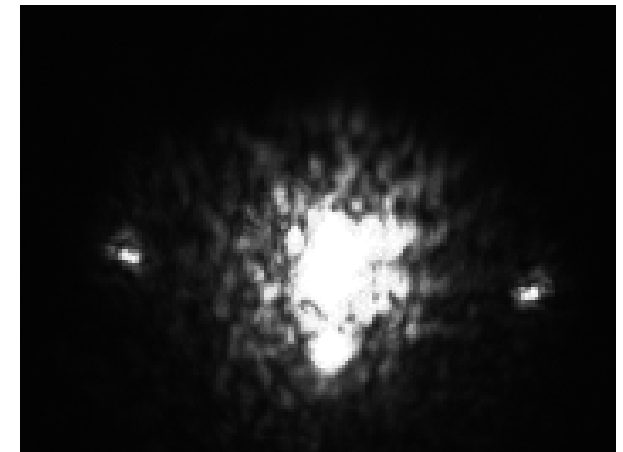
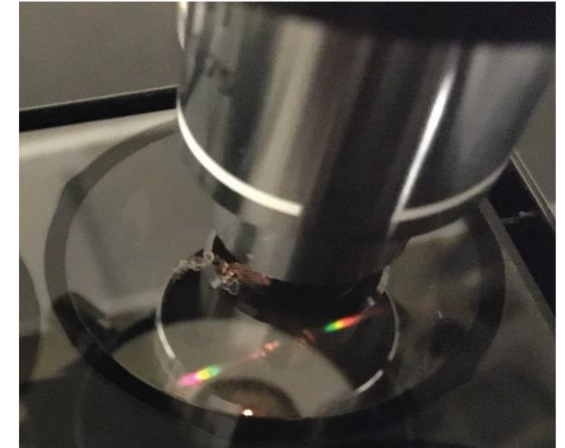
Implosion Fabrication Diffraction Grating



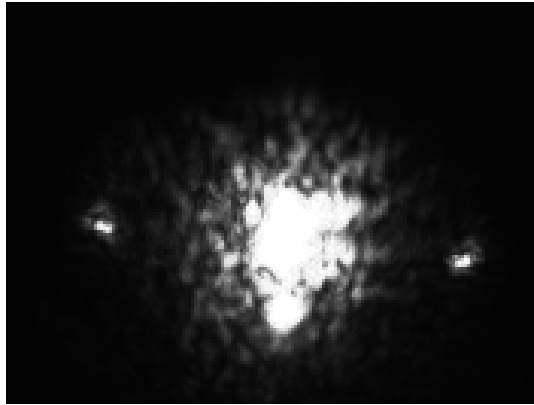
100 μm



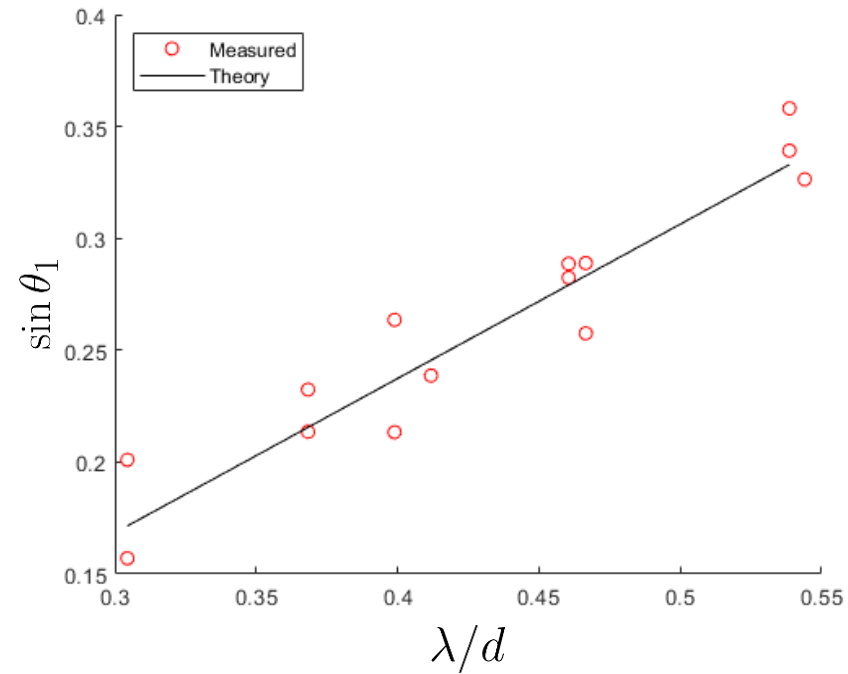
10 μm



Implosion Fabrication Diffraction Grating

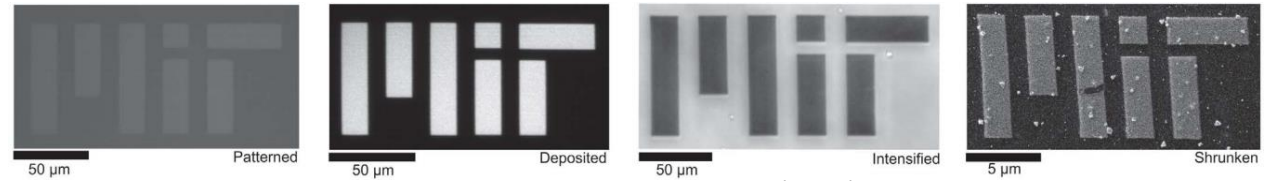


Grating Period [nm]	Wavelength[nm]	
943	520	600
1114	520	600
1286	520	600
1457	-	600
1629	-	600

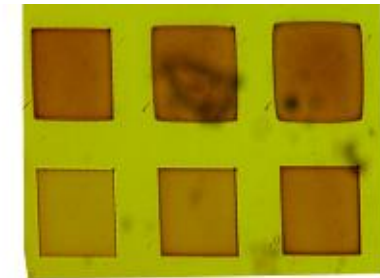
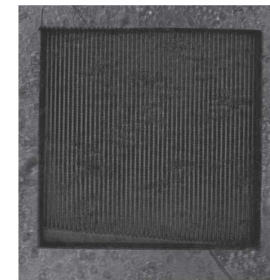


Summary

- Implosion Fabrication
 - Free standing nanostructures
 - Maintain structure aspect ratio
 - Tunable reflectivity



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Future Development

Materials

Gold

Silicon

Diamond

Quantum Dots

More Complex Devices

Multi-material devices

Continuously varying index

- Varying laser power during patterning

Utilize gel shrinkage to actively tune device parameters.

- Conductivity
- Index