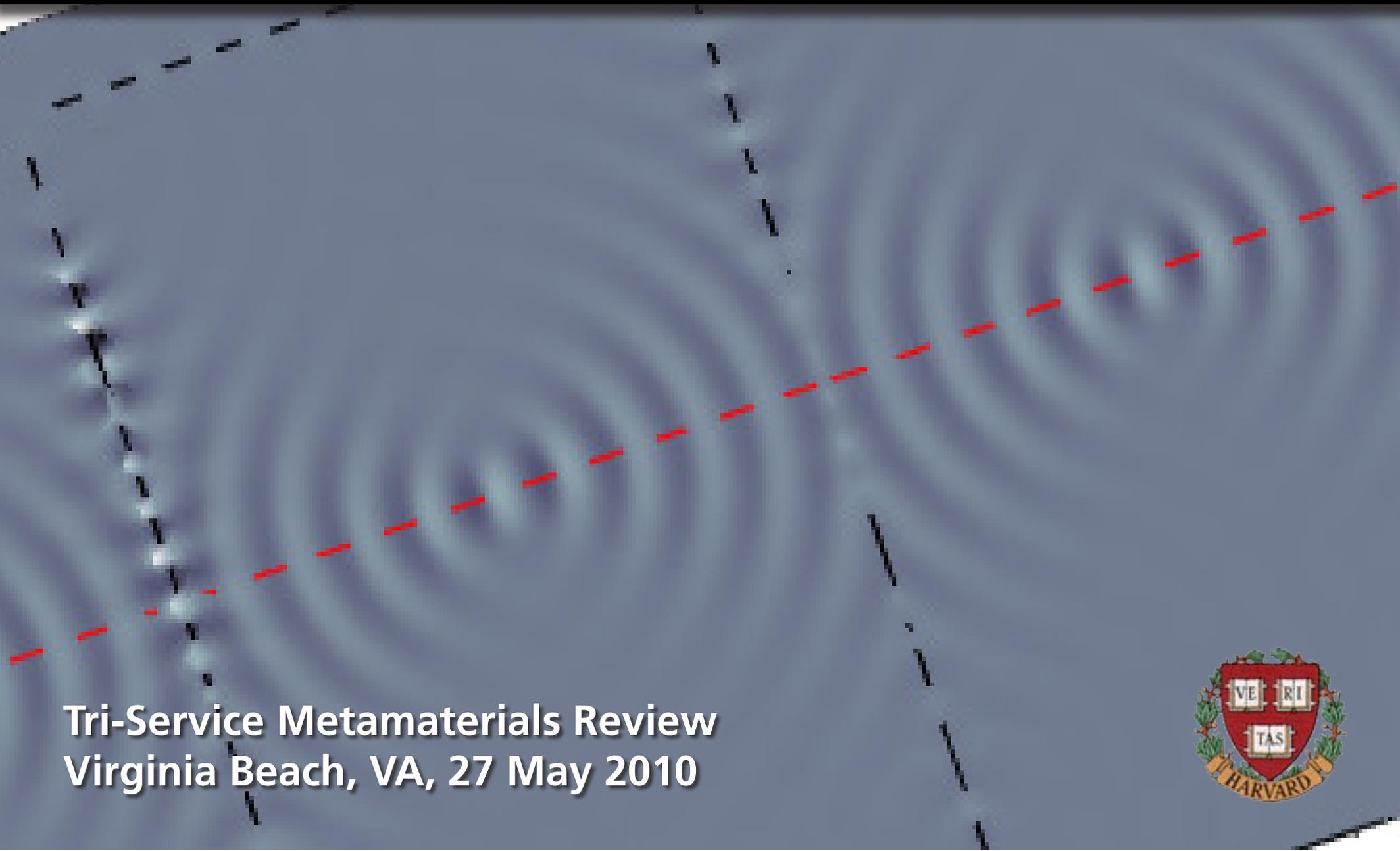


# Direct writing of metallic structures for metamaterial applications

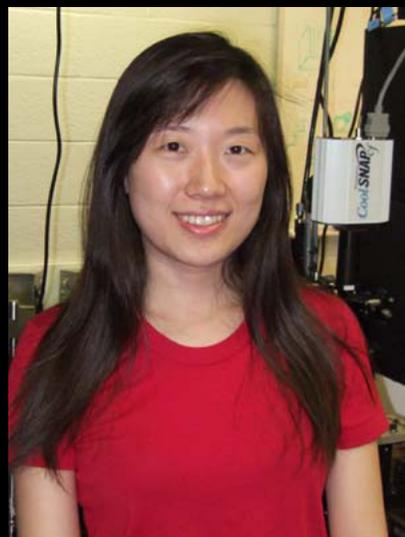


Tri-Service Metamaterials Review  
Virginia Beach, VA, 27 May 2010





**Kevin Vora**



**Seungyeon Kang**



**Michael Moebius**



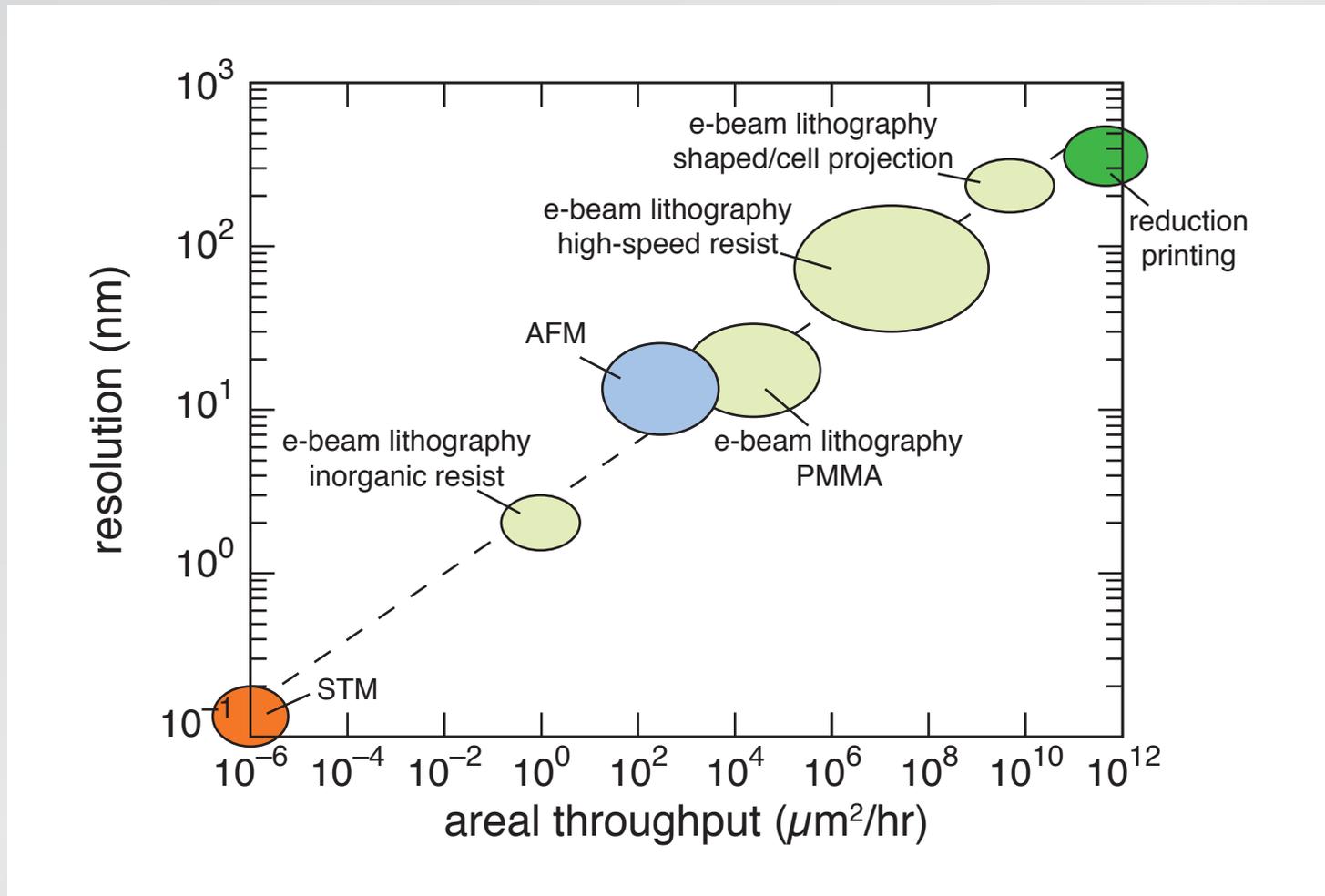
**Eric Mazur**

# Introduction

**direct-write, submicrometer, 3D fabrication technique**

# Introduction

## resolution-throughput tradeoff

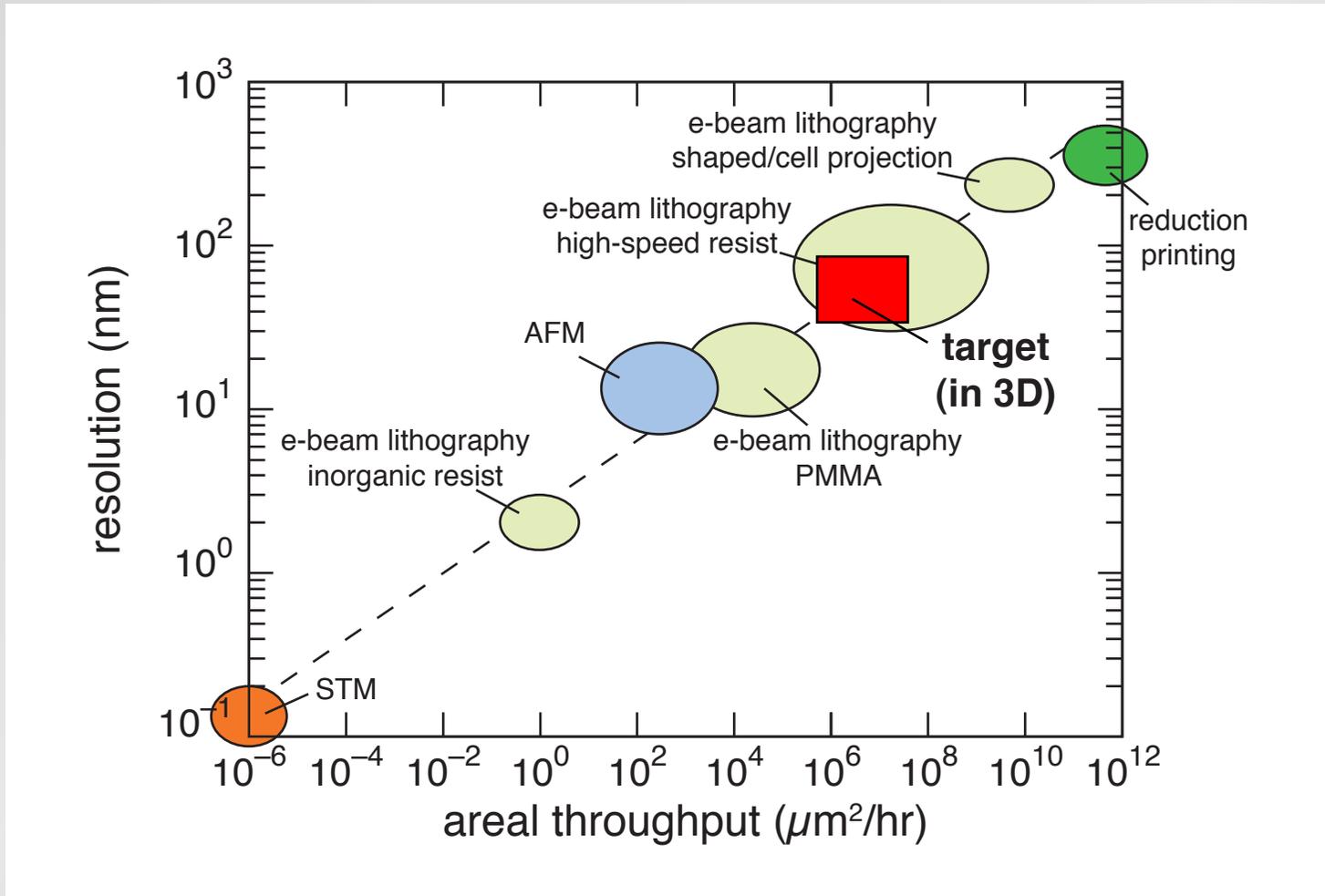


# Introduction

**most of these techniques difficult to scale to 3D**

# Introduction

## resolution-throughput tradeoff

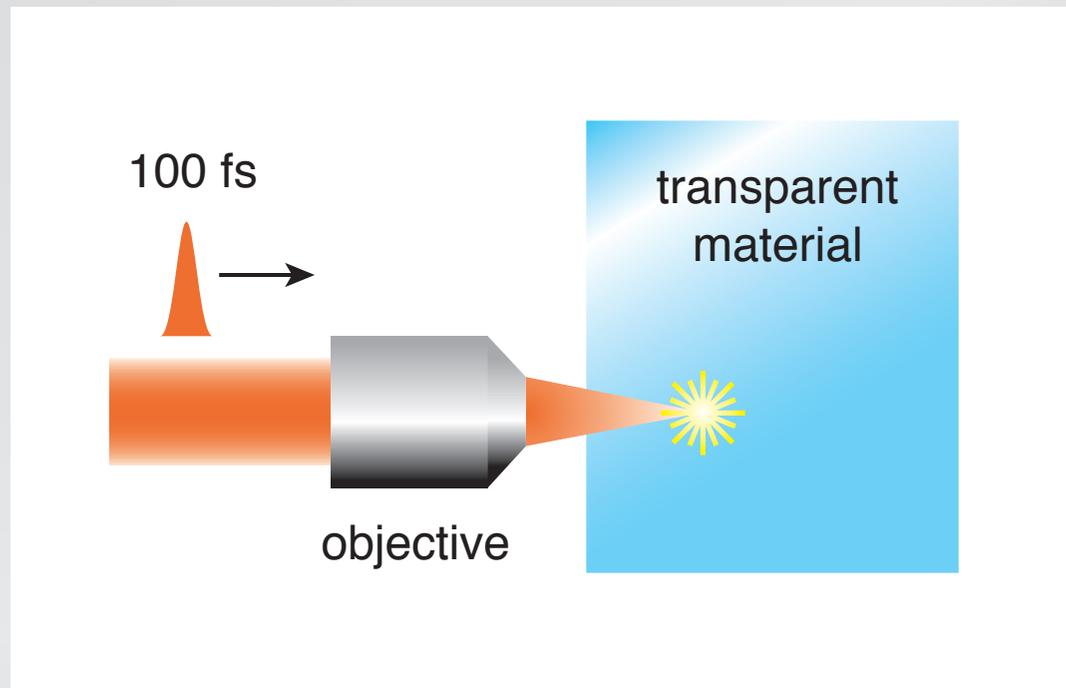


# Outline

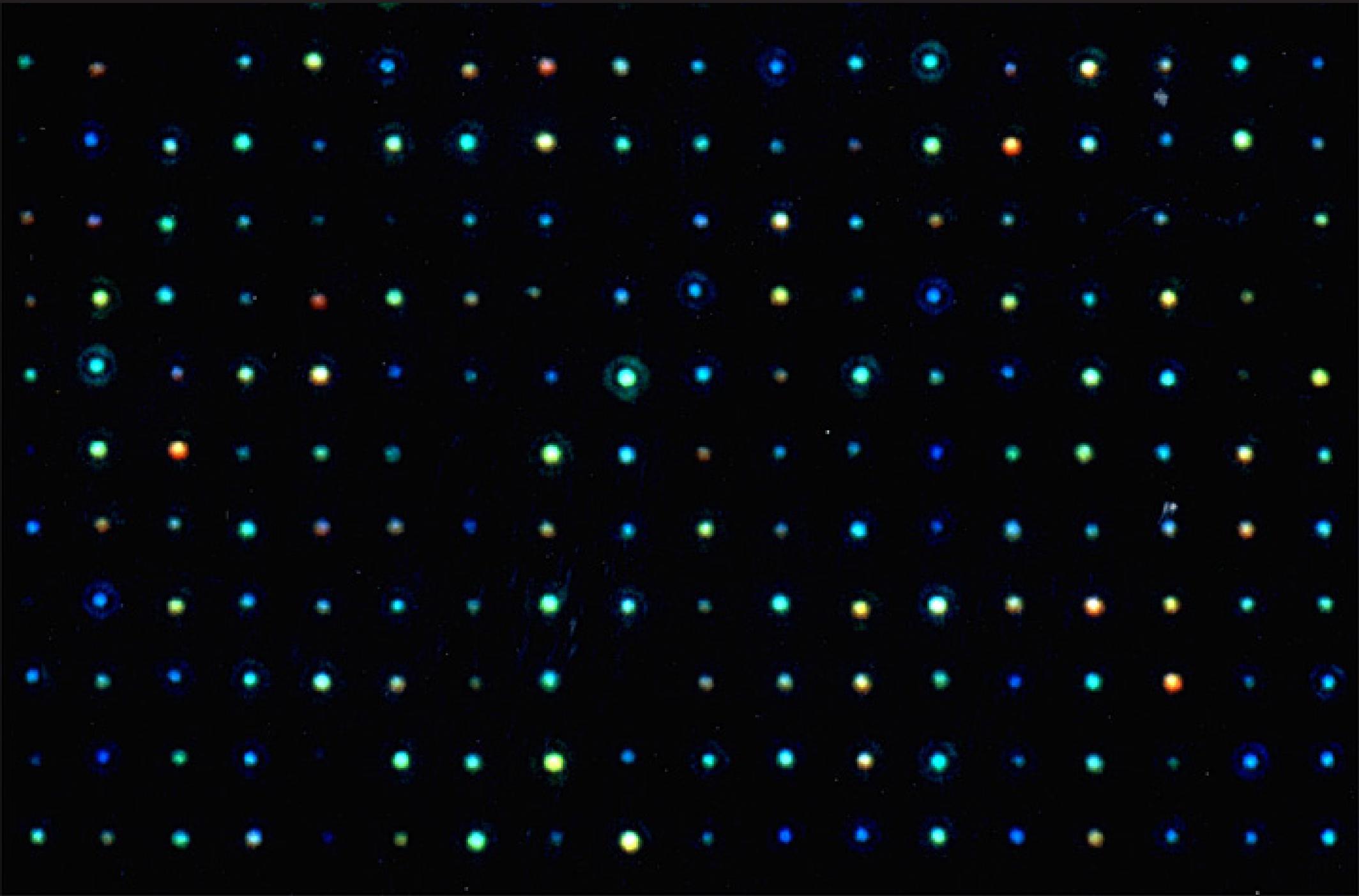
- femtosecond micromachining
- direct writing metal structures
- preliminary results

# Femtosecond micromachining

focus laser beam inside material



# Femtosecond micromachining

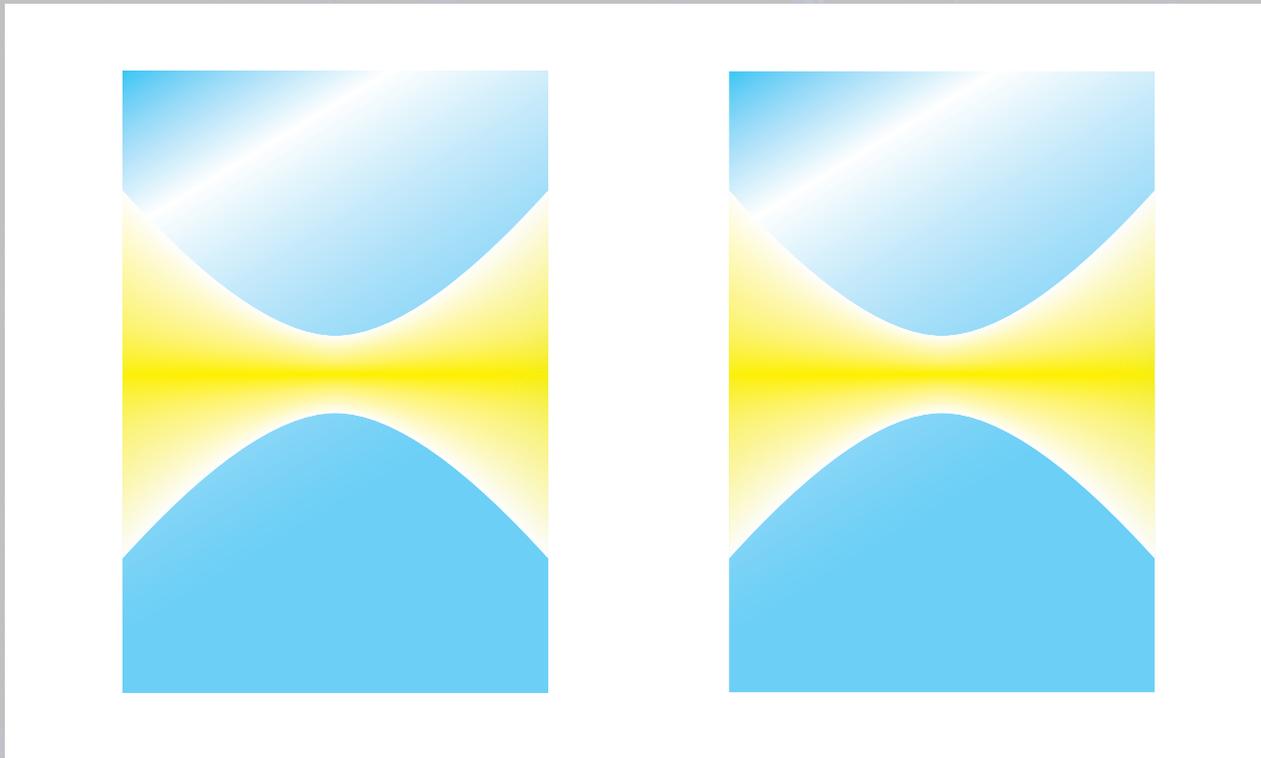


# Femtosecond micromachining

photon energy  $<$  bandgap  $\longrightarrow$  nonlinear interaction

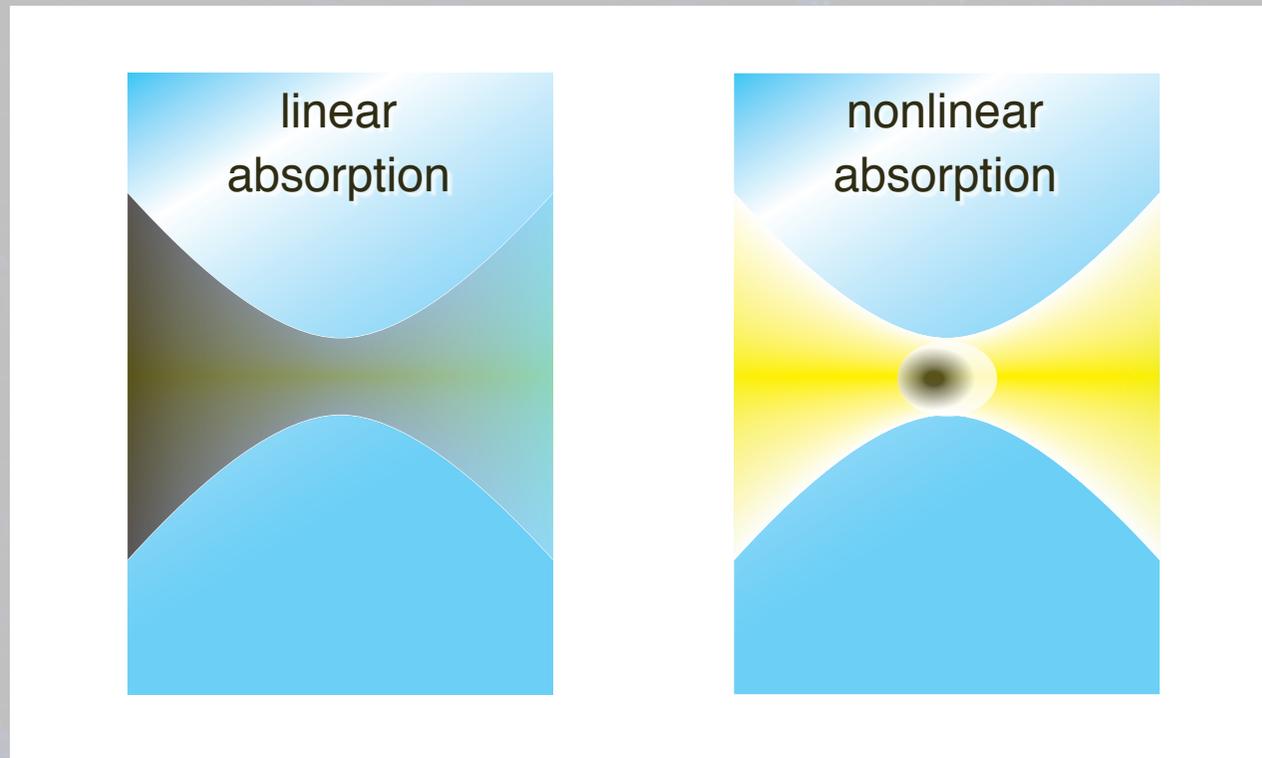
# Femtosecond micromachining

nonlinear interaction provides bulk confinement



# Femtosecond micromachining

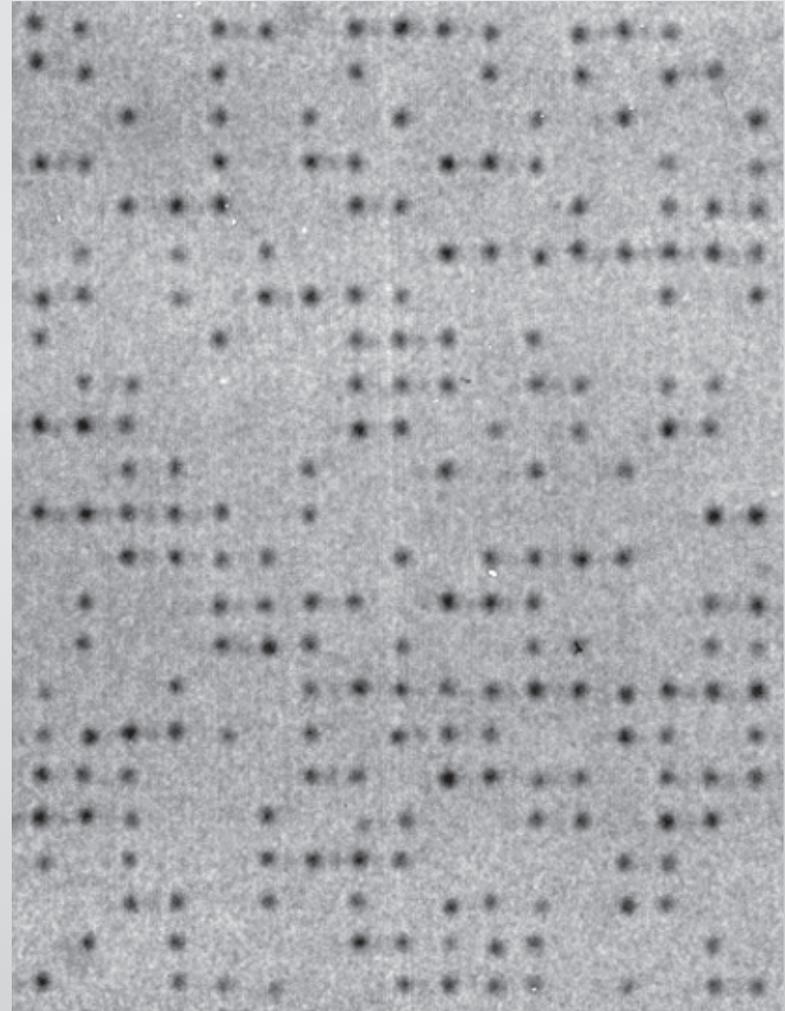
nonlinear interaction provides bulk confinement



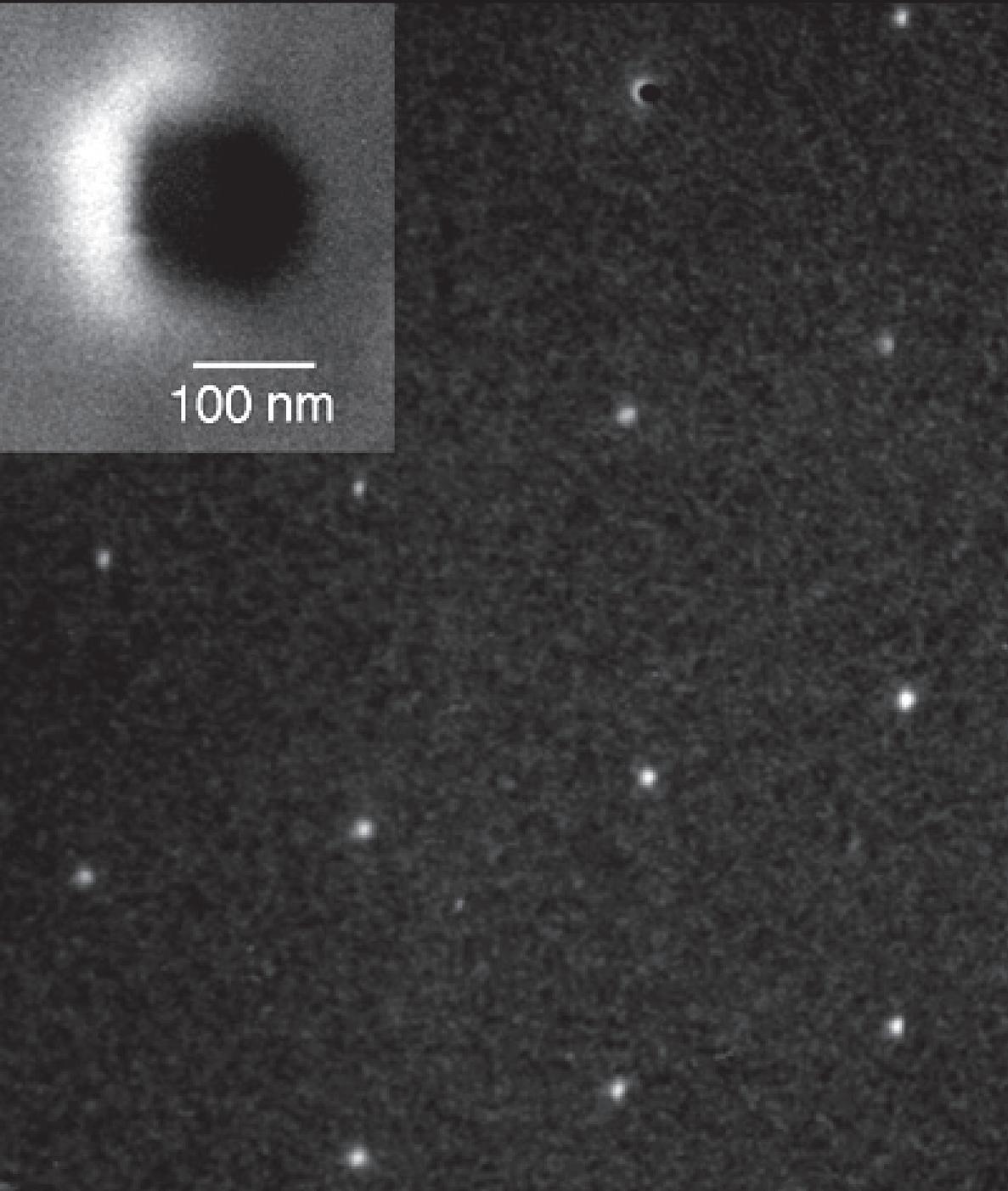
# Femtosecond micromachining

**Some applications:**

- **data storage**
- **wave guides**
- **microfluidics**



# Femtosecond micromachining

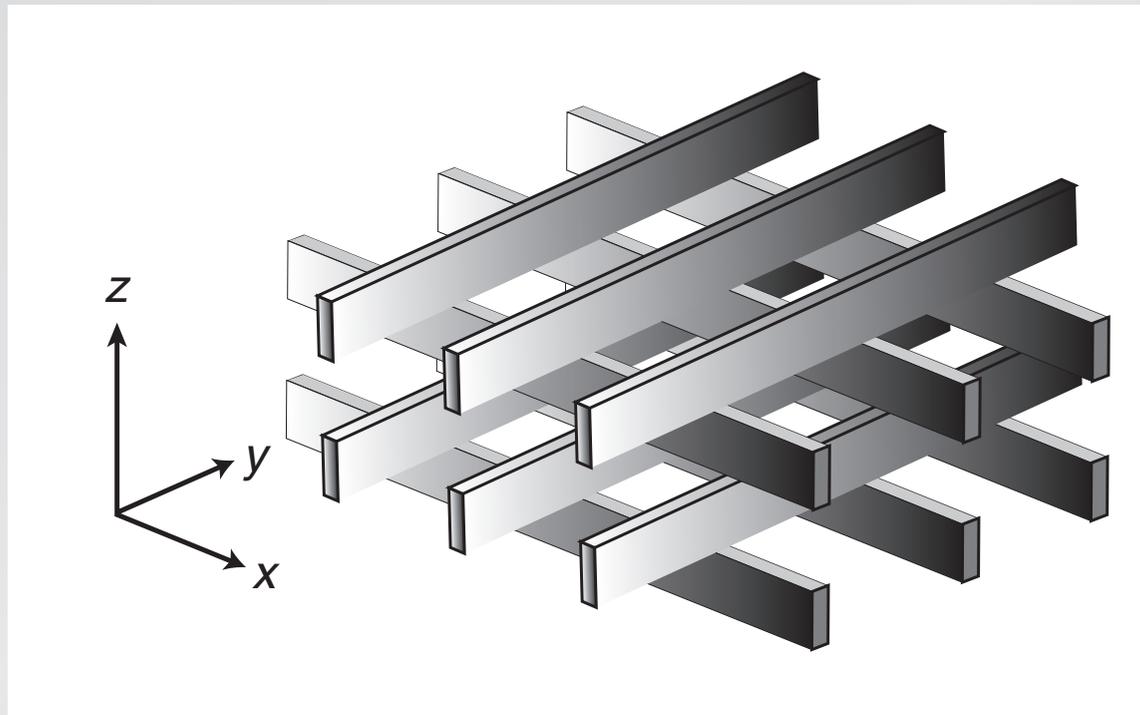


## SEM & AFM:

- 100-nm cavities
- little colateral damage

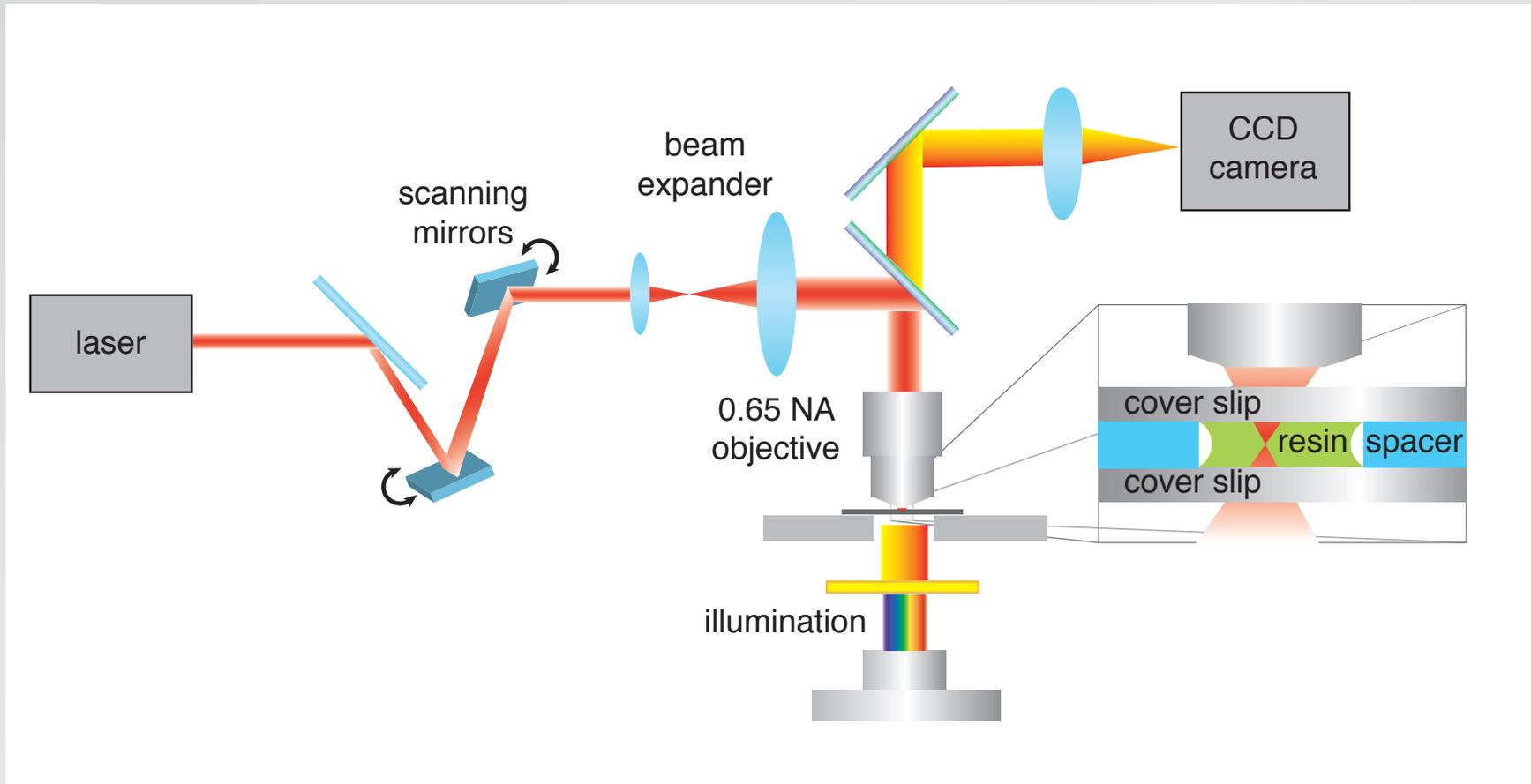
# Femtosecond micromachining

wood pile structure



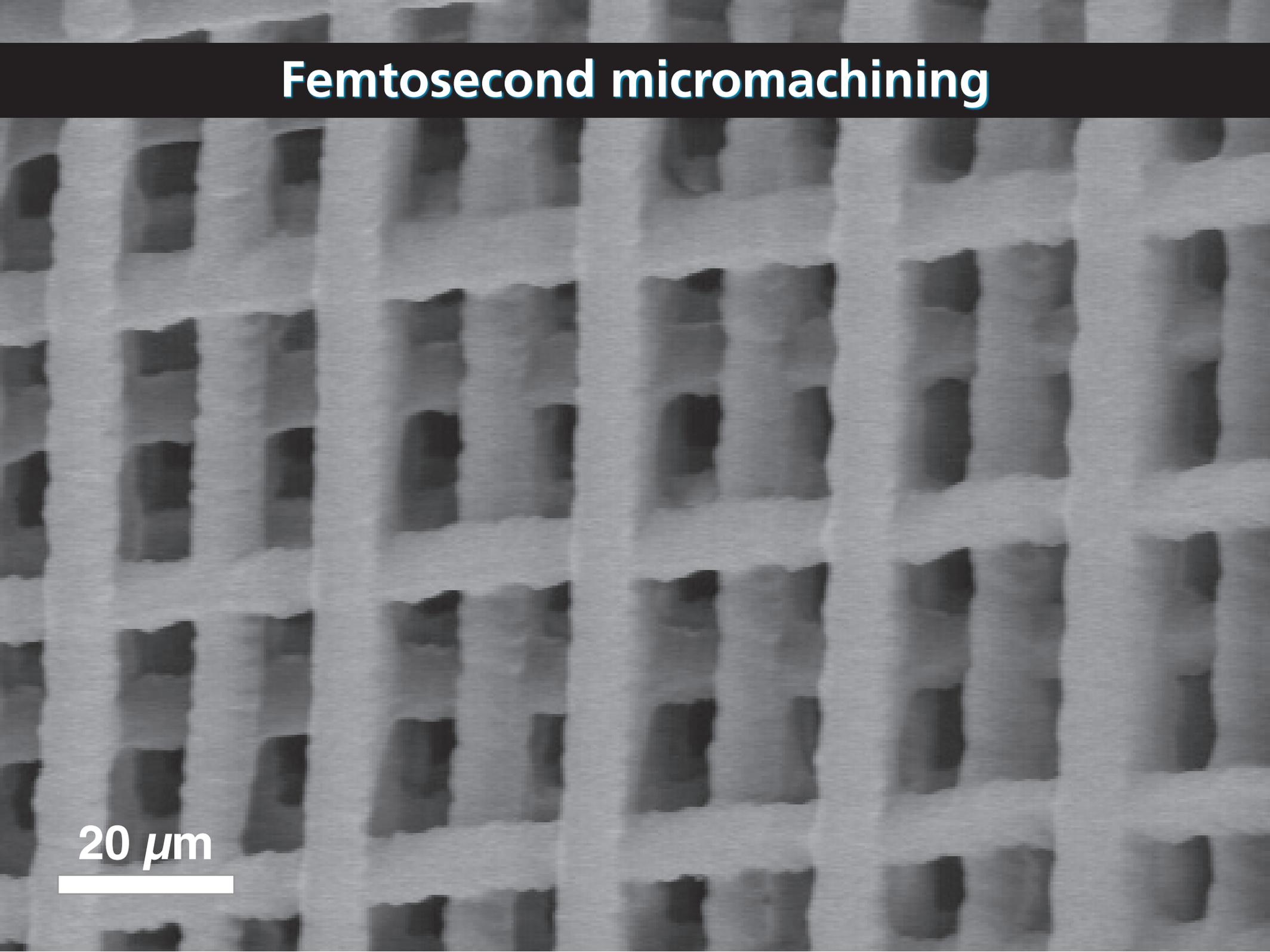
# Femtosecond micromachining

## 2-photon polymerization setup



# Femtosecond micromachining

20  $\mu\text{m}$

A scanning electron microscope (SEM) image showing a highly regular, periodic lattice structure. The structure consists of a grid of interconnected rectangular or square elements, forming a porous, mesh-like material. The elements are arranged in a staggered pattern, creating a series of small, interconnected voids. The overall appearance is that of a precision-machined microstructure. A white horizontal scale bar is located in the bottom-left corner, labeled "20 μm".

# Femtosecond micromachining



# Femtosecond micromachining



# Femtosecond micromachining

## Points to keep in mind:

- bulk/3D technique
- resolution down to 100 nm
- scalable

*Nat. Phot.* 2, 219 (2008)



# Outline

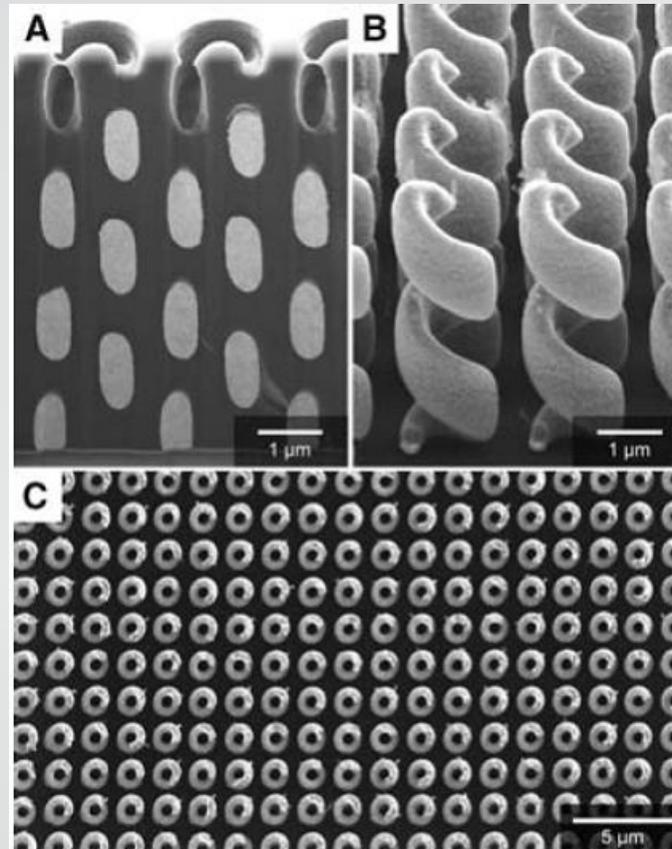
- femtosecond micromachining
- direct writing metal structures
- preliminary results

# Direct writing metal structures

high resolution two-photon polymerization demonstrated

# Direct writing metal structures

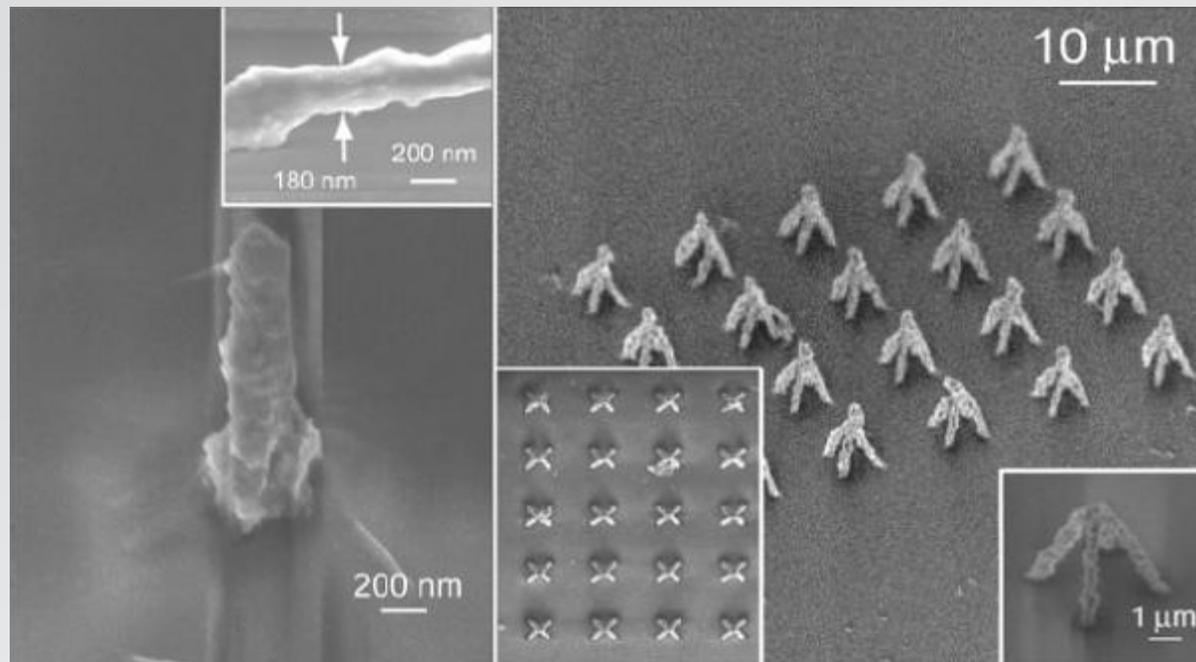
direct writing in positive photo resist & electroplating



J.K. Gansel, *et al.*, *Science* 325, 1513 (2009)

# Direct writing metal structures

two-photon reduction of metal ions



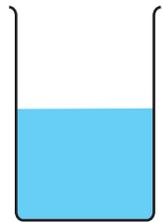
Y.-Y. Cao, *et al.*, *Small* 5, 1144 (2009)

# Direct writing metal structures

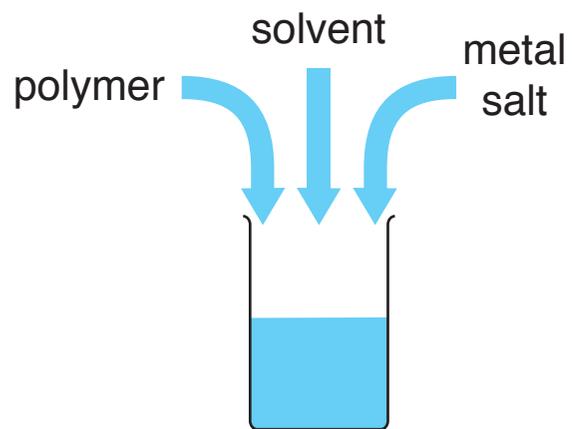
**Our goals:**

- **direct-writing of metallic structure**
- **accelerate reduction process**
- **enable large area/volume fabrication**

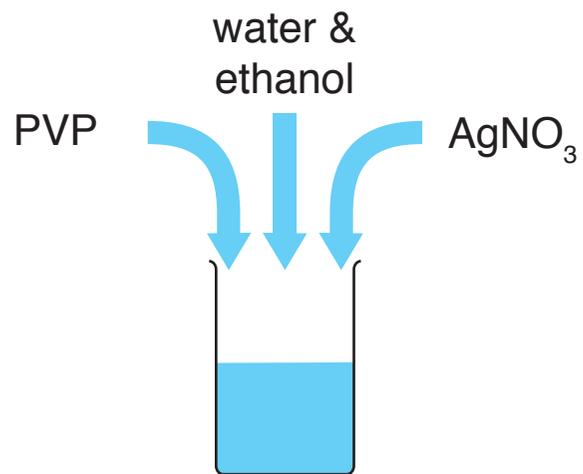
# Direct writing metal structures



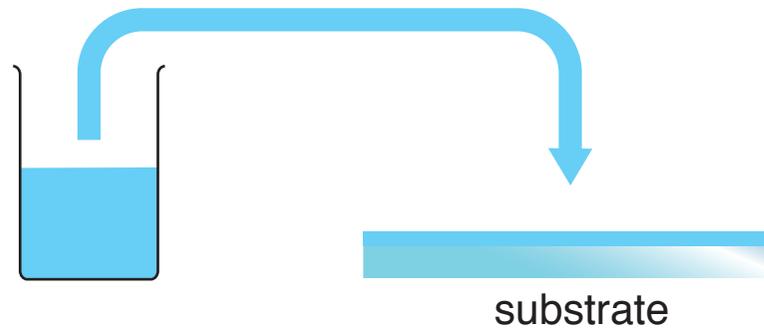
# Direct writing metal structures



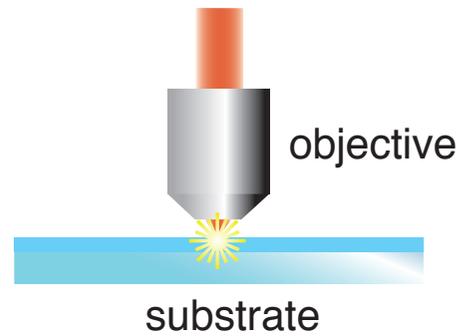
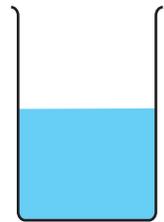
# Direct writing metal structures



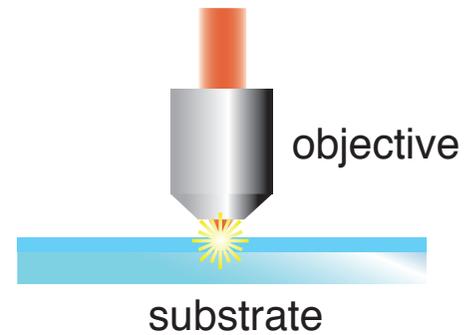
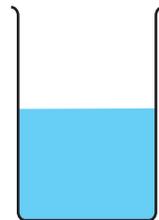
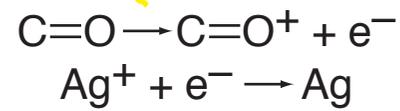
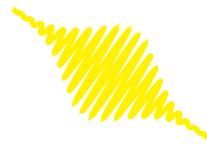
# Direct writing metal structures



# Direct writing metal structures



# Direct writing metal structures



# Direct writing metal structures

Currently investigating:

- chemistry
- energy delivery
- post-fabrication treatment

# Direct writing metal structures

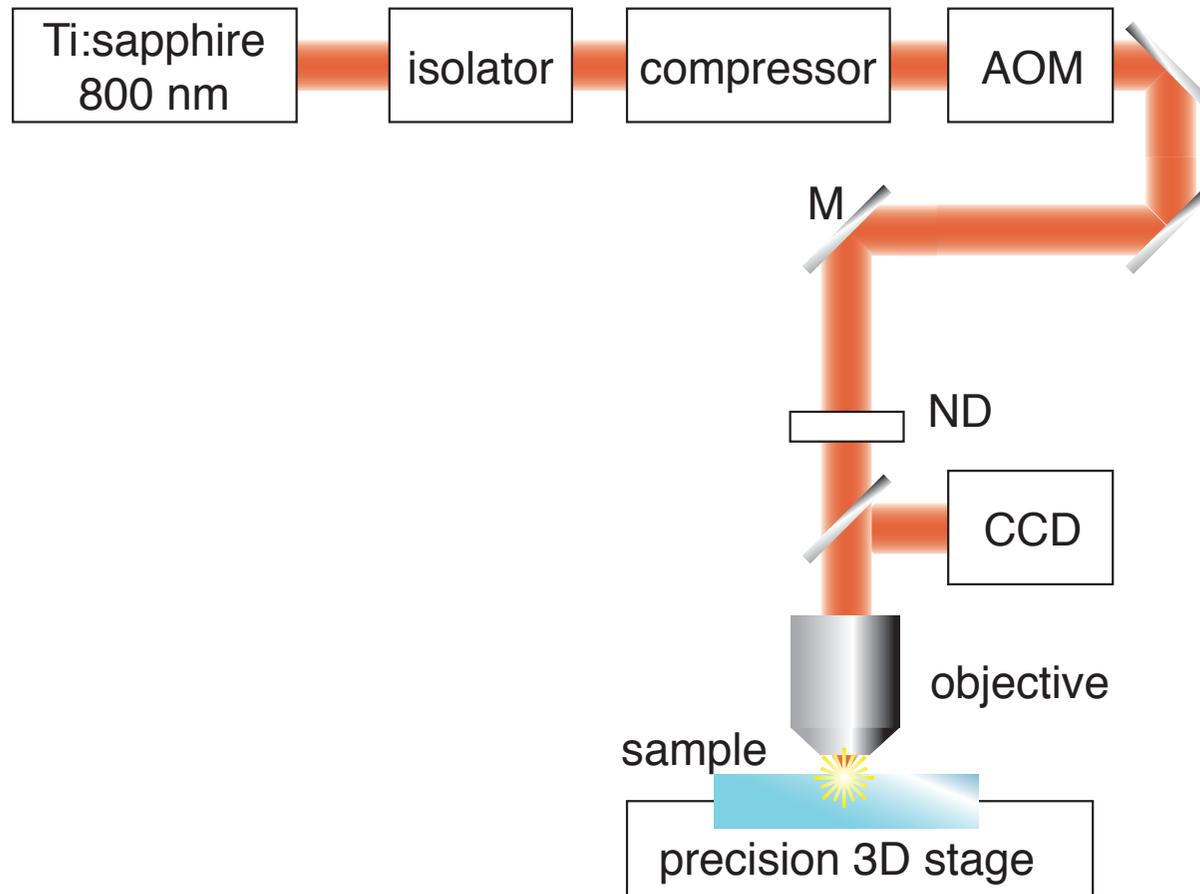
**Points to keep in mind:**

- **bulk/3D technique**
- **100-nm resolution possible**
- **no clean room required**

# Outline

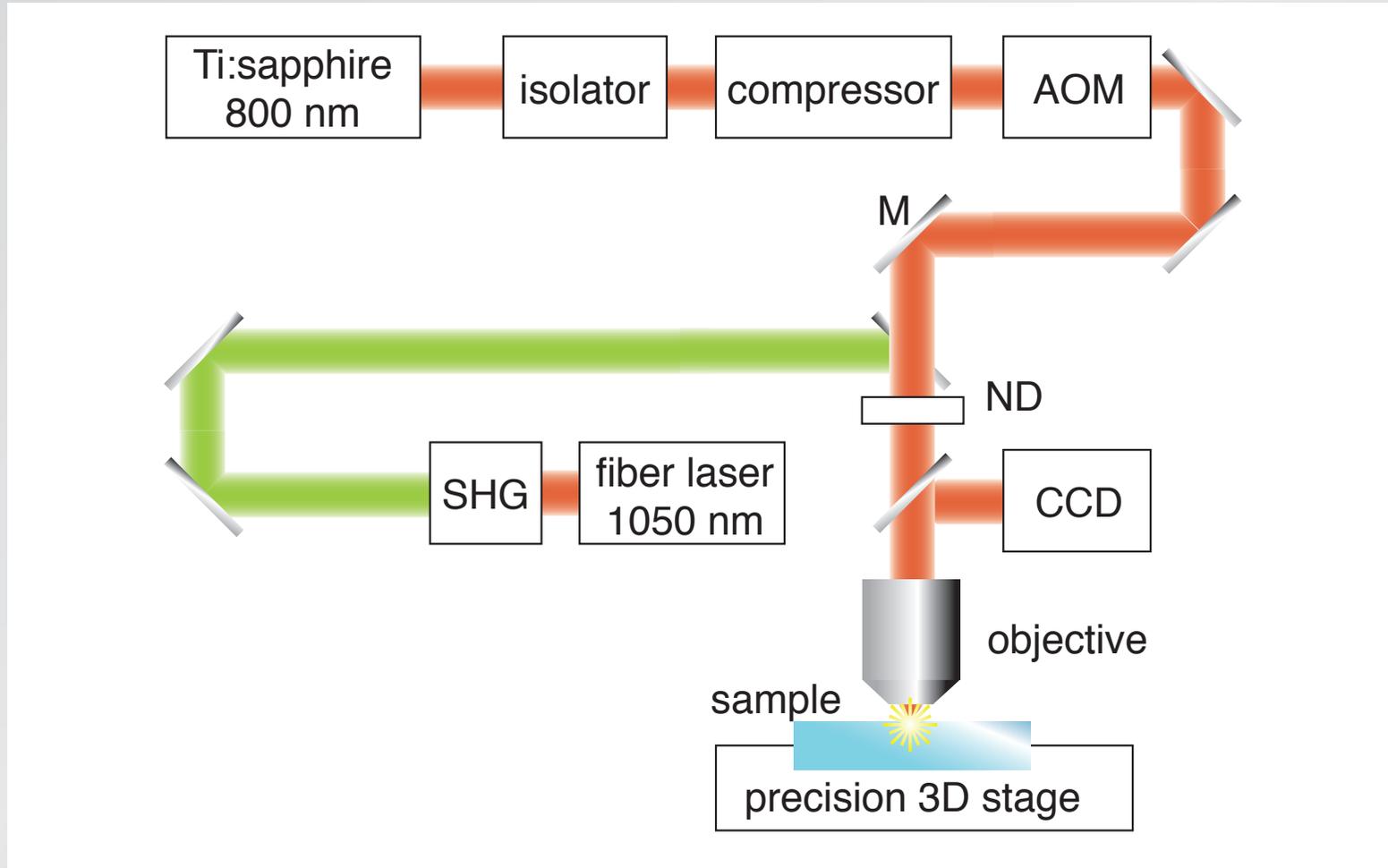
- femtosecond micromachining
- direct writing metal structures
- preliminary results

# Preliminary results



# Preliminary results

can also write using doubled fiber laser

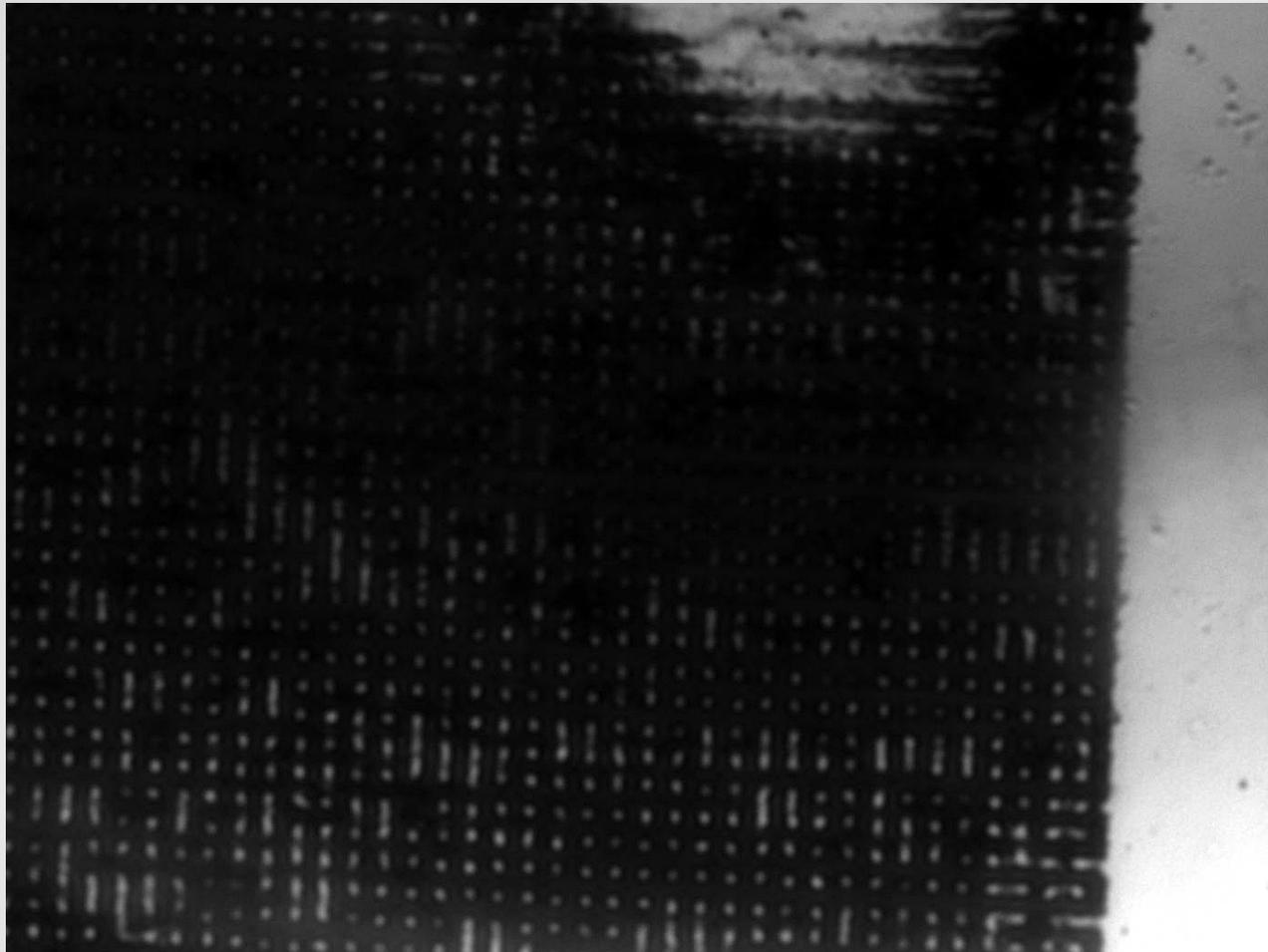


# Preliminary results



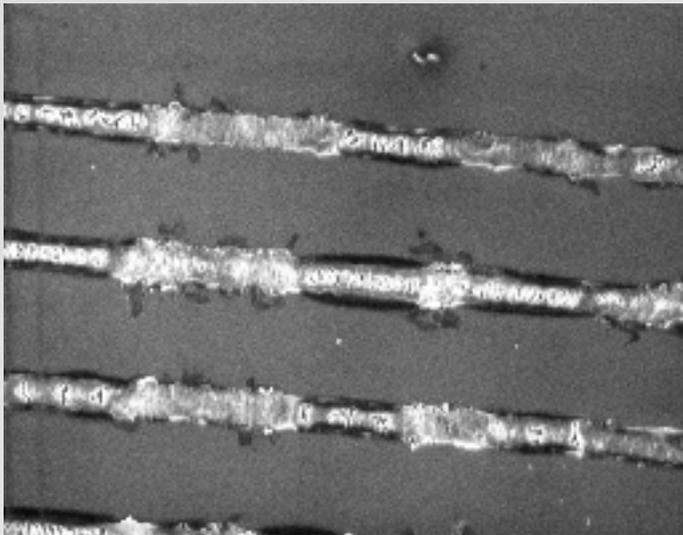
# Preliminary results

*in situ* optical picture of silver woodpile structure



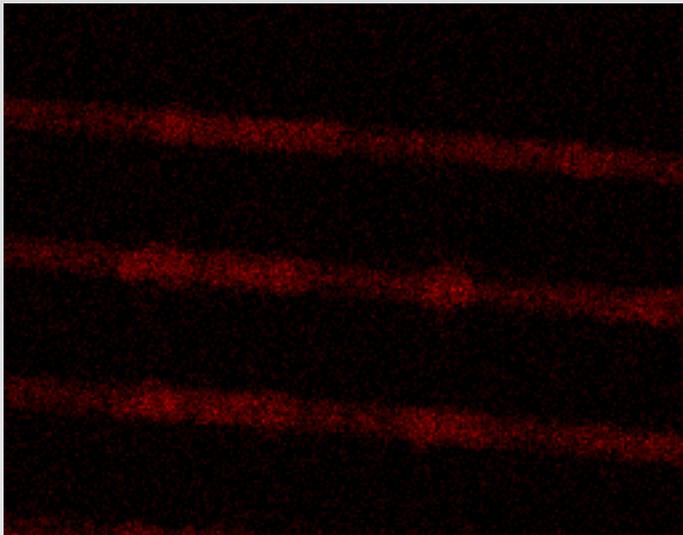
# Preliminary results

## EDS analysis



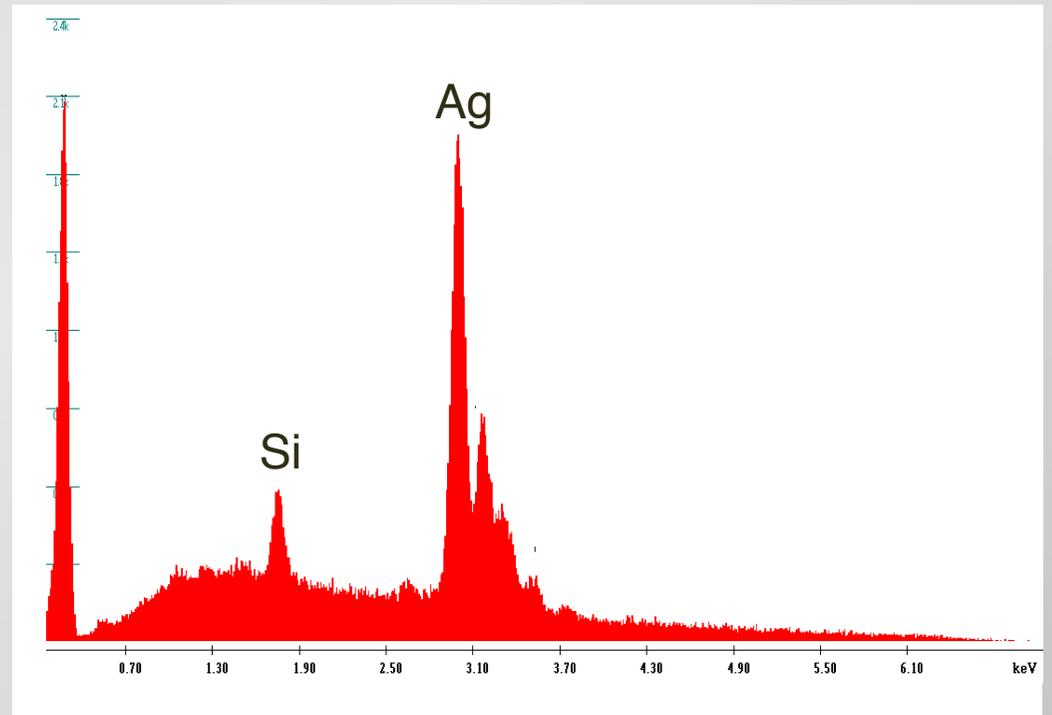
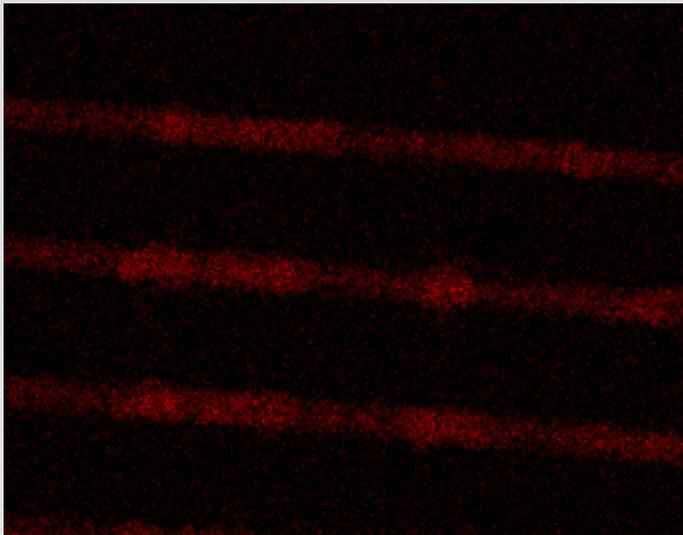
# Preliminary results

## EDS analysis



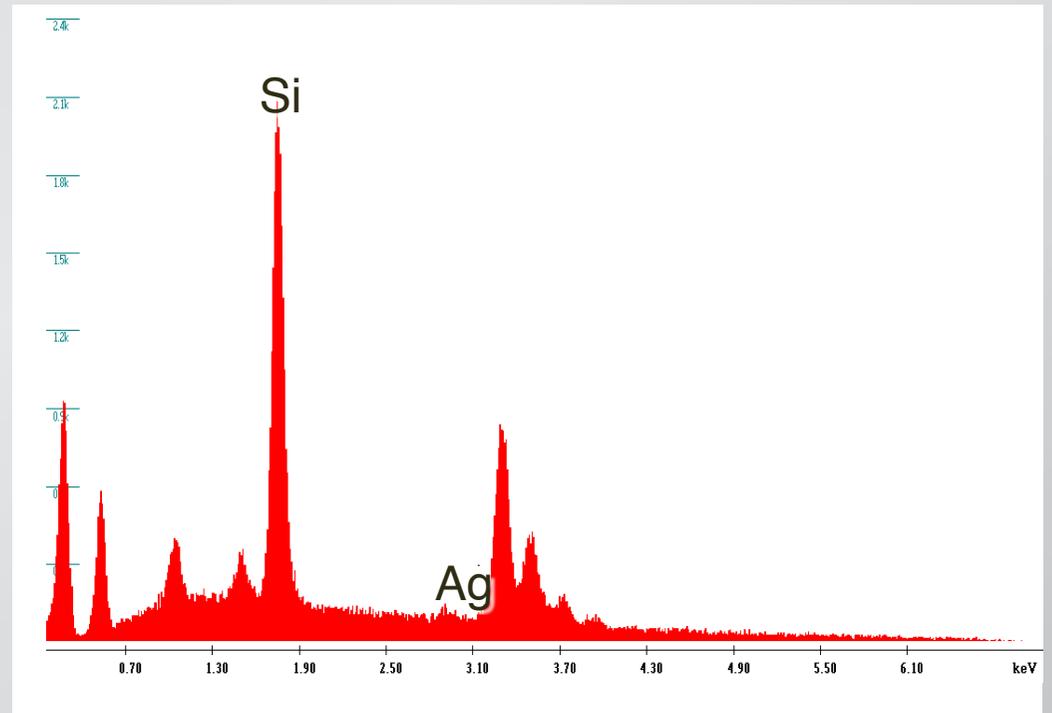
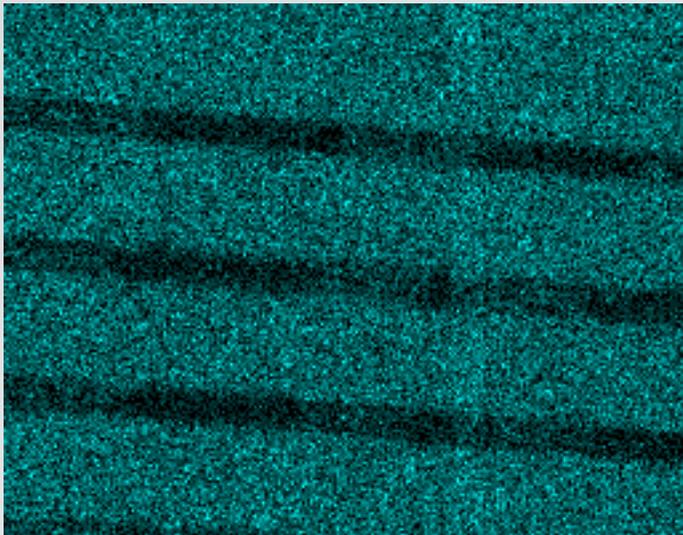
# Preliminary results

## EDS analysis



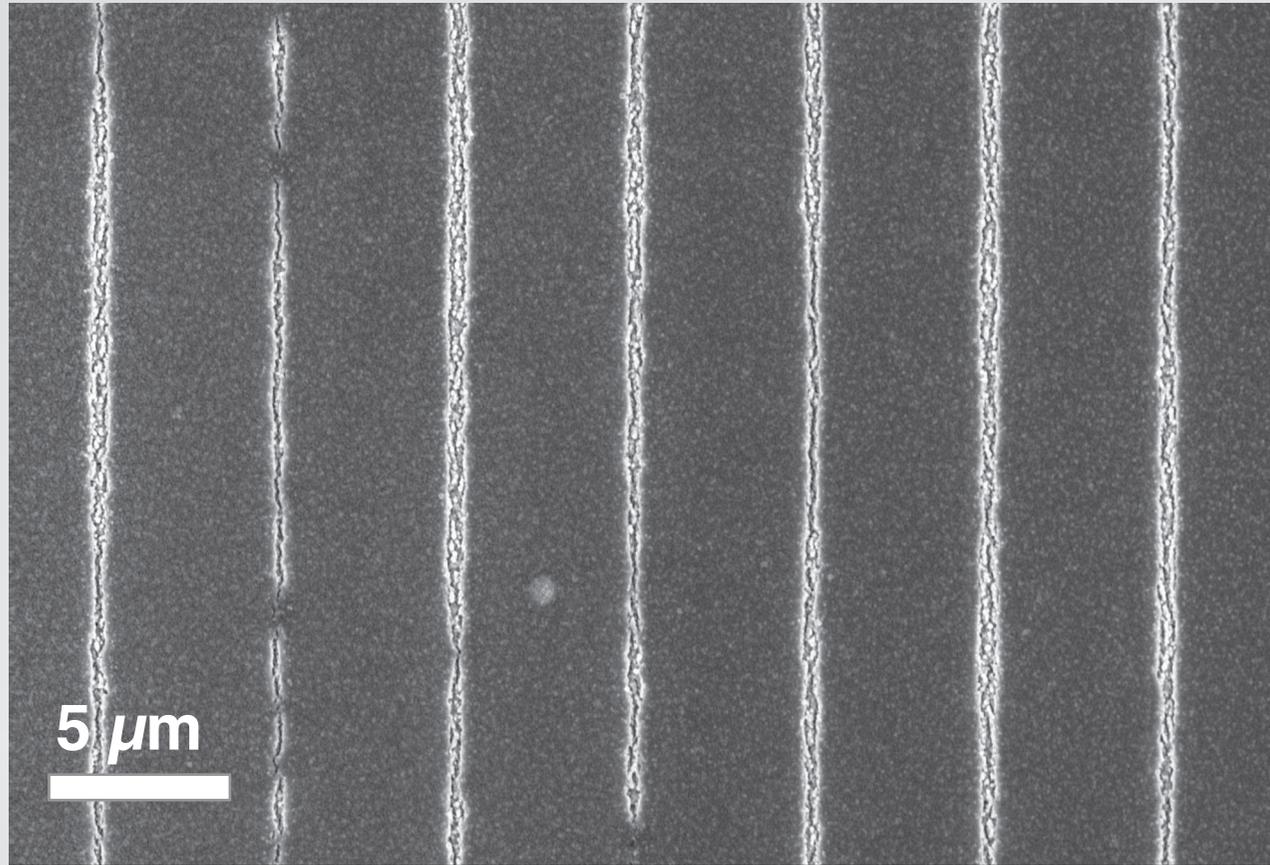
# Preliminary results

## EDS analysis



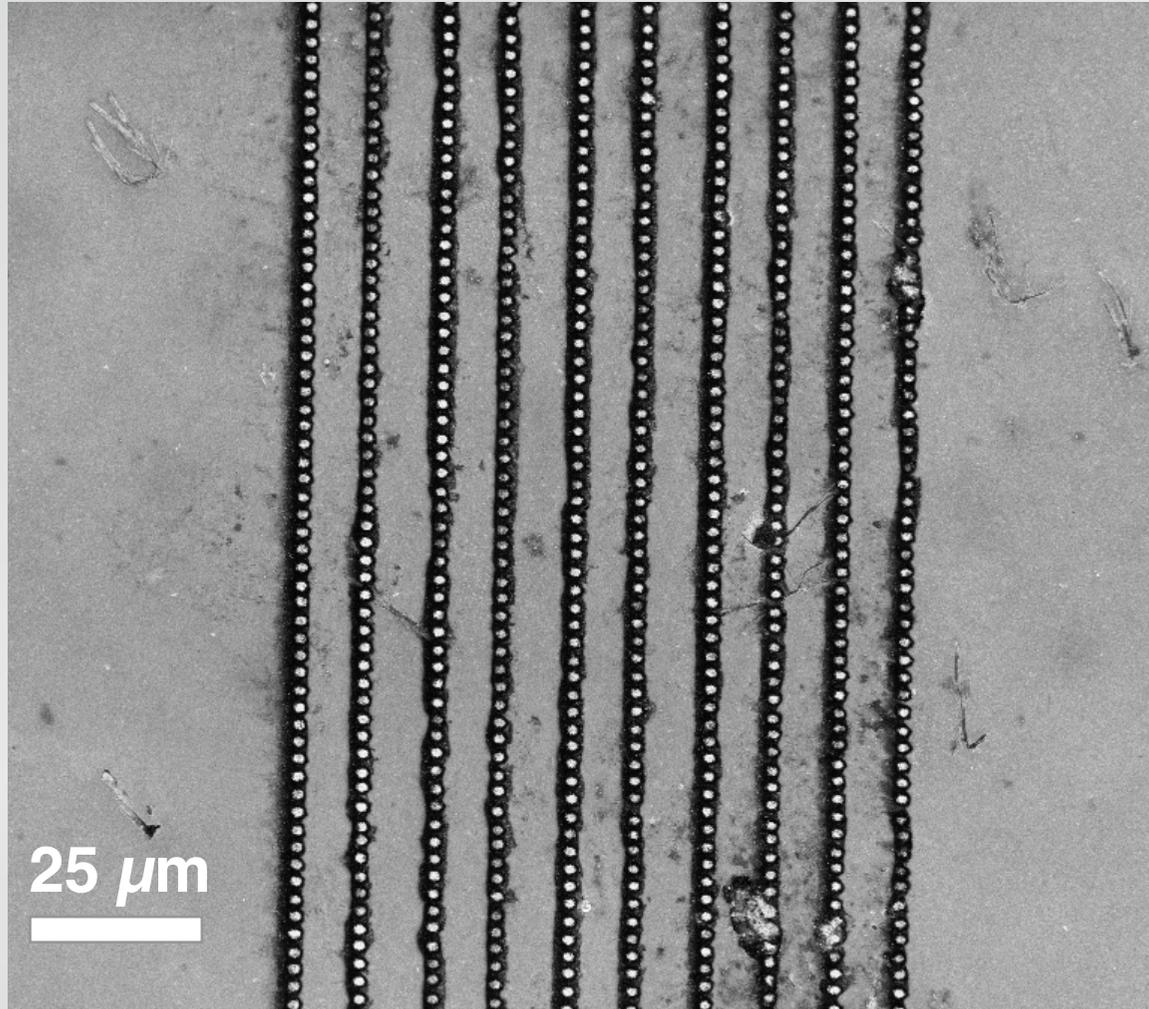
# Preliminary results

submicrometer lines



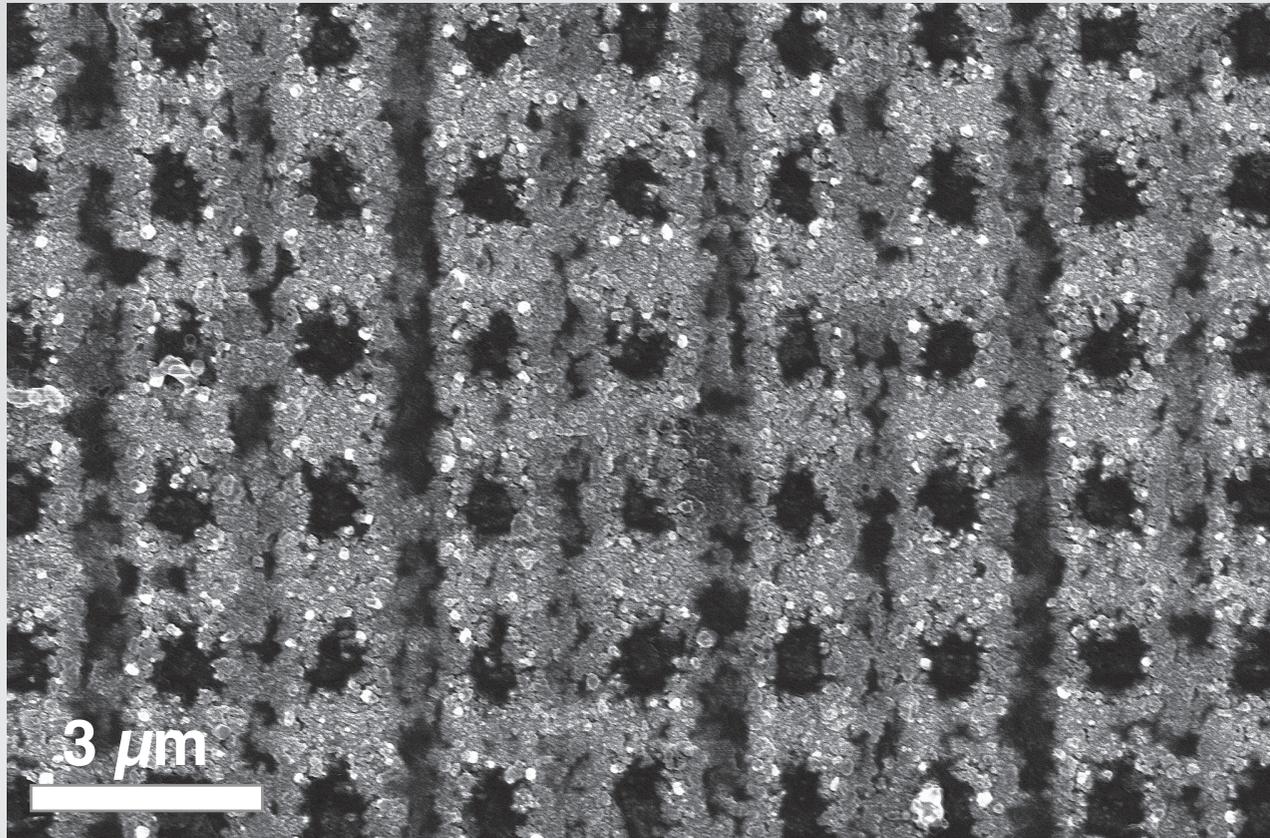
# Preliminary results

lines of dots



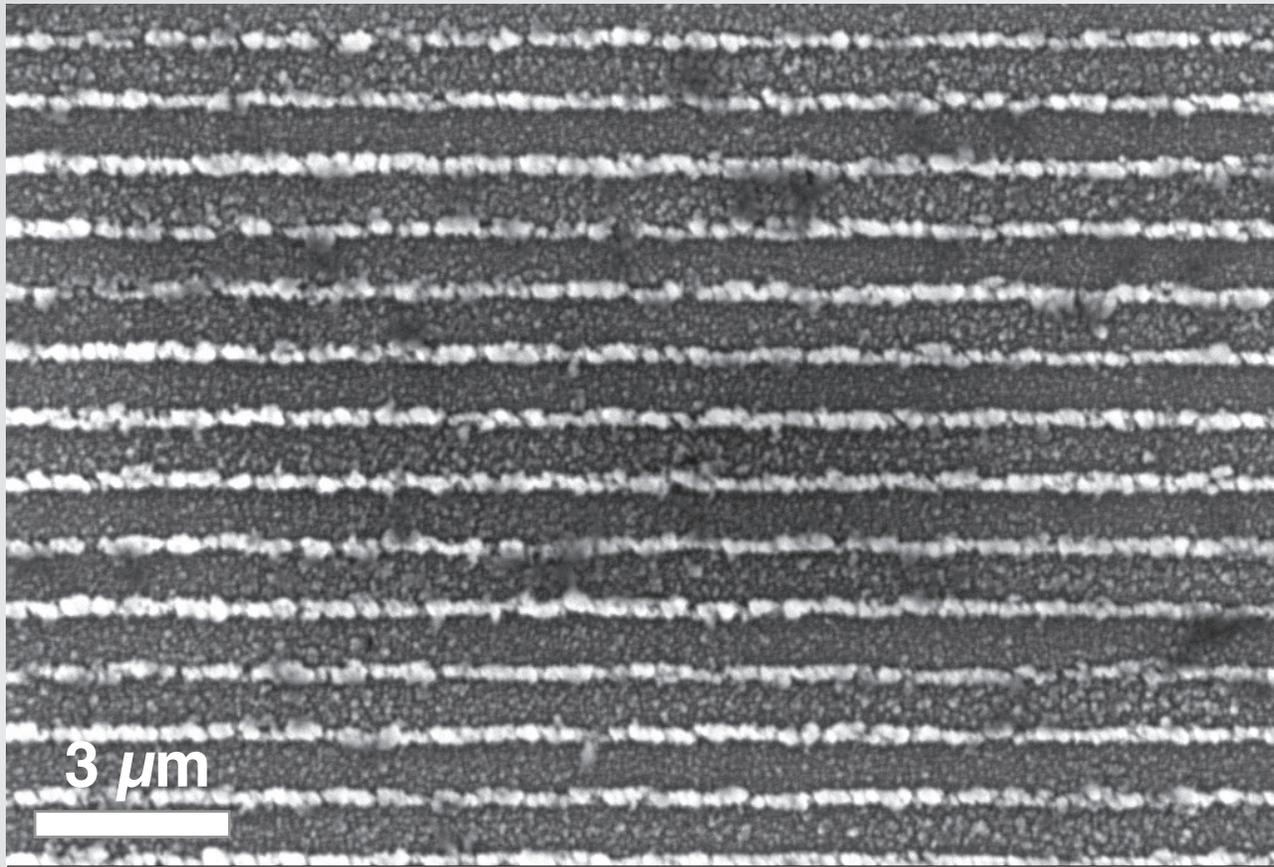
# Preliminary results

ring structures



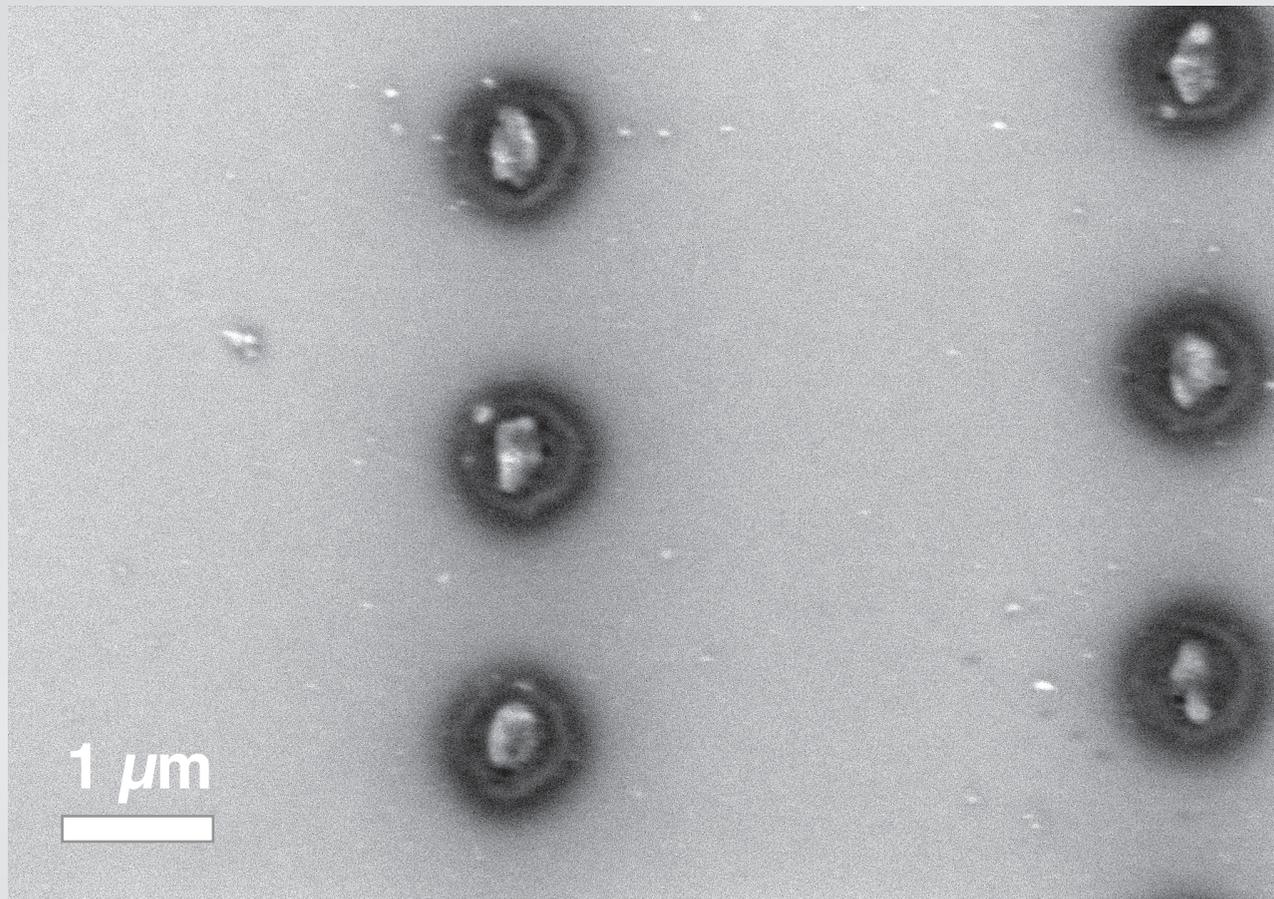
# Preliminary results

submicrometer gold lines



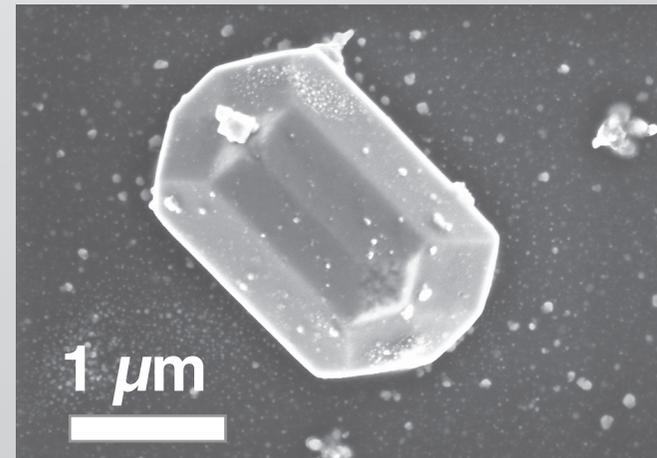
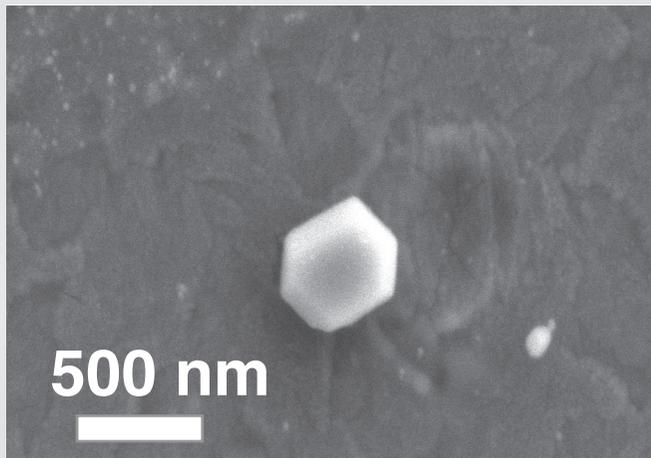
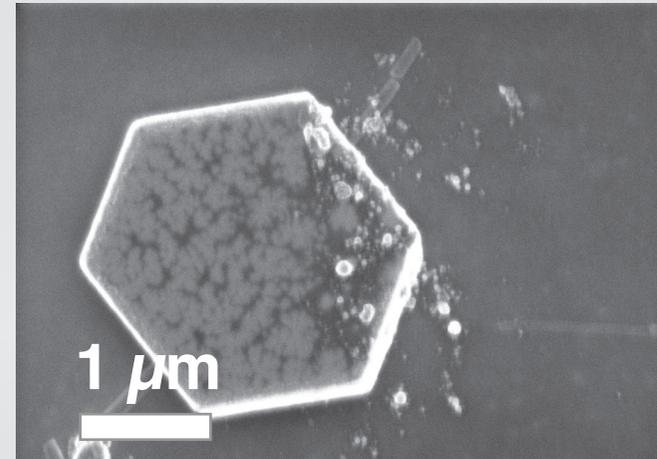
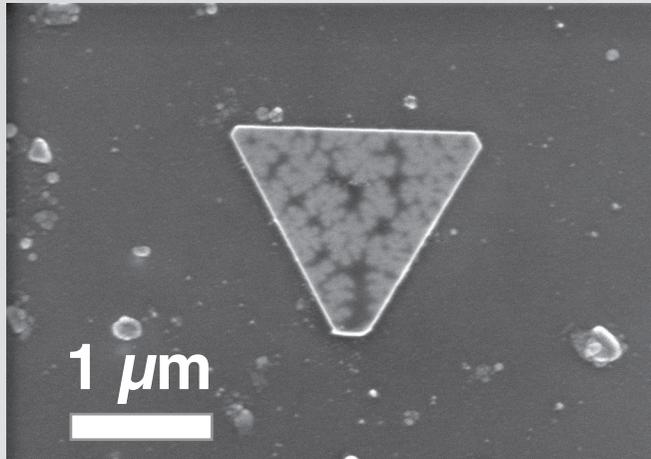
# Preliminary results

submicrometer dots



# Preliminary results

assortment of interesting shapes

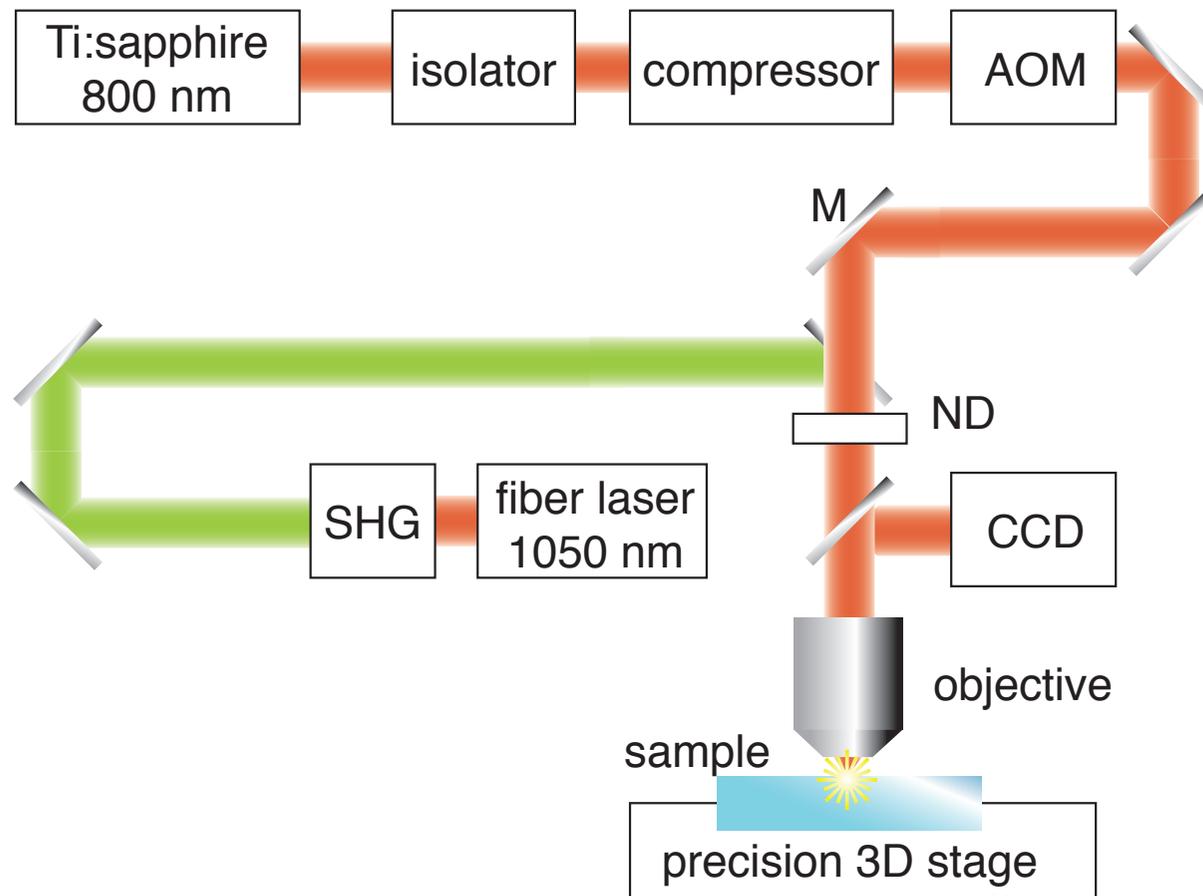


# Preliminary results

## Future work:

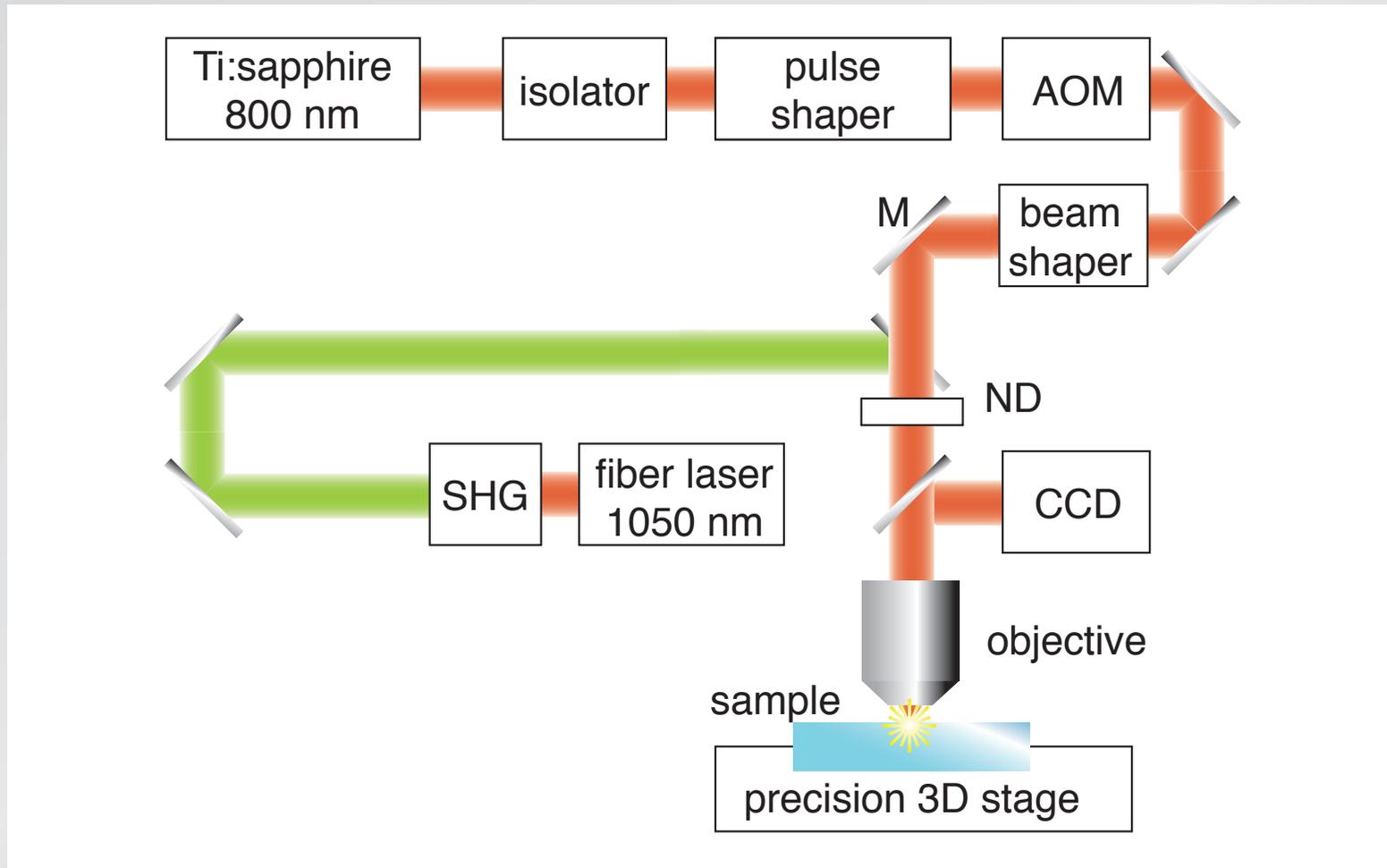
- chemistry
- writing process
- post processing

# Preliminary results



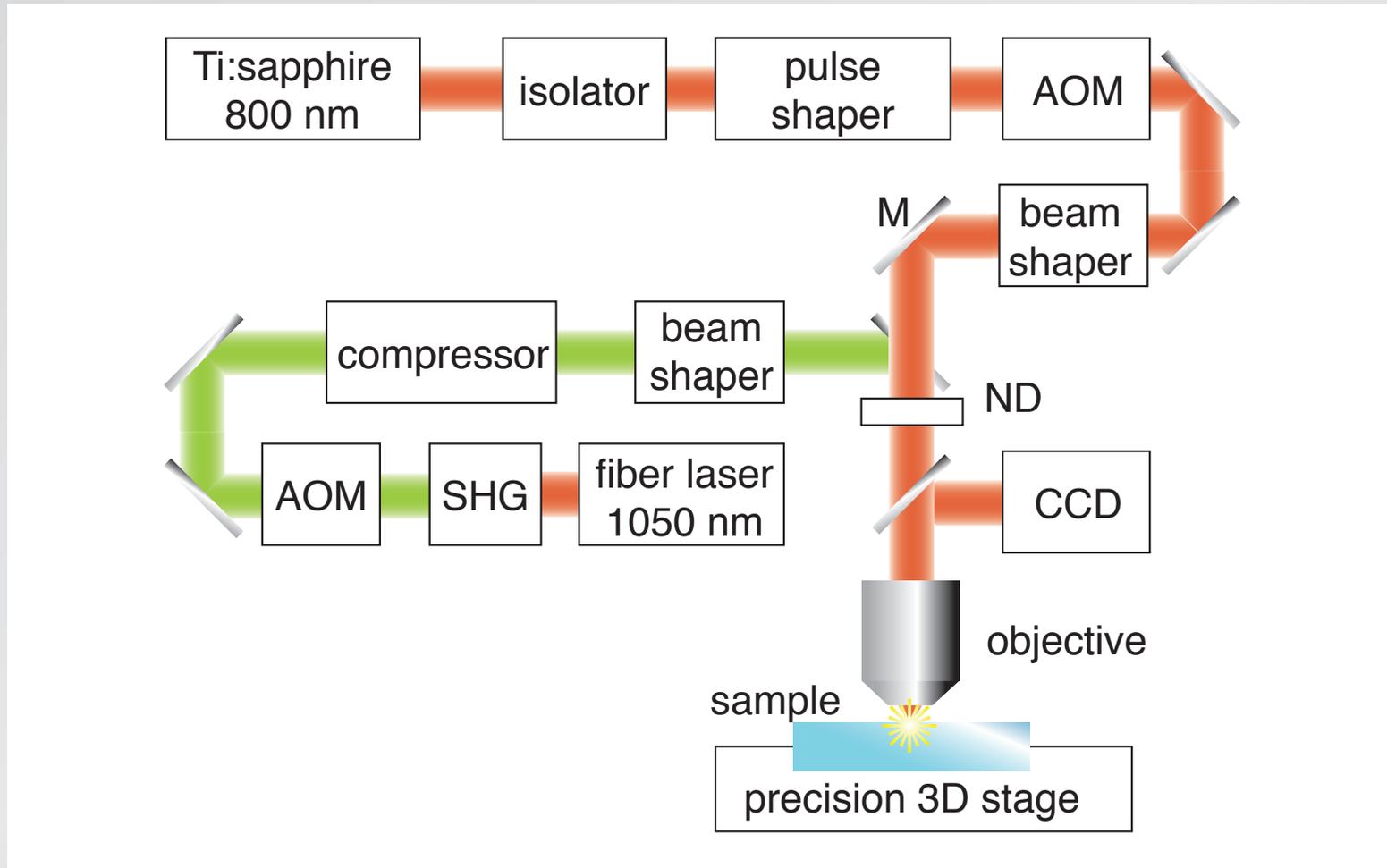
# Preliminary results

planned: add pulse and beam shapers to Ti:sapphire beam line



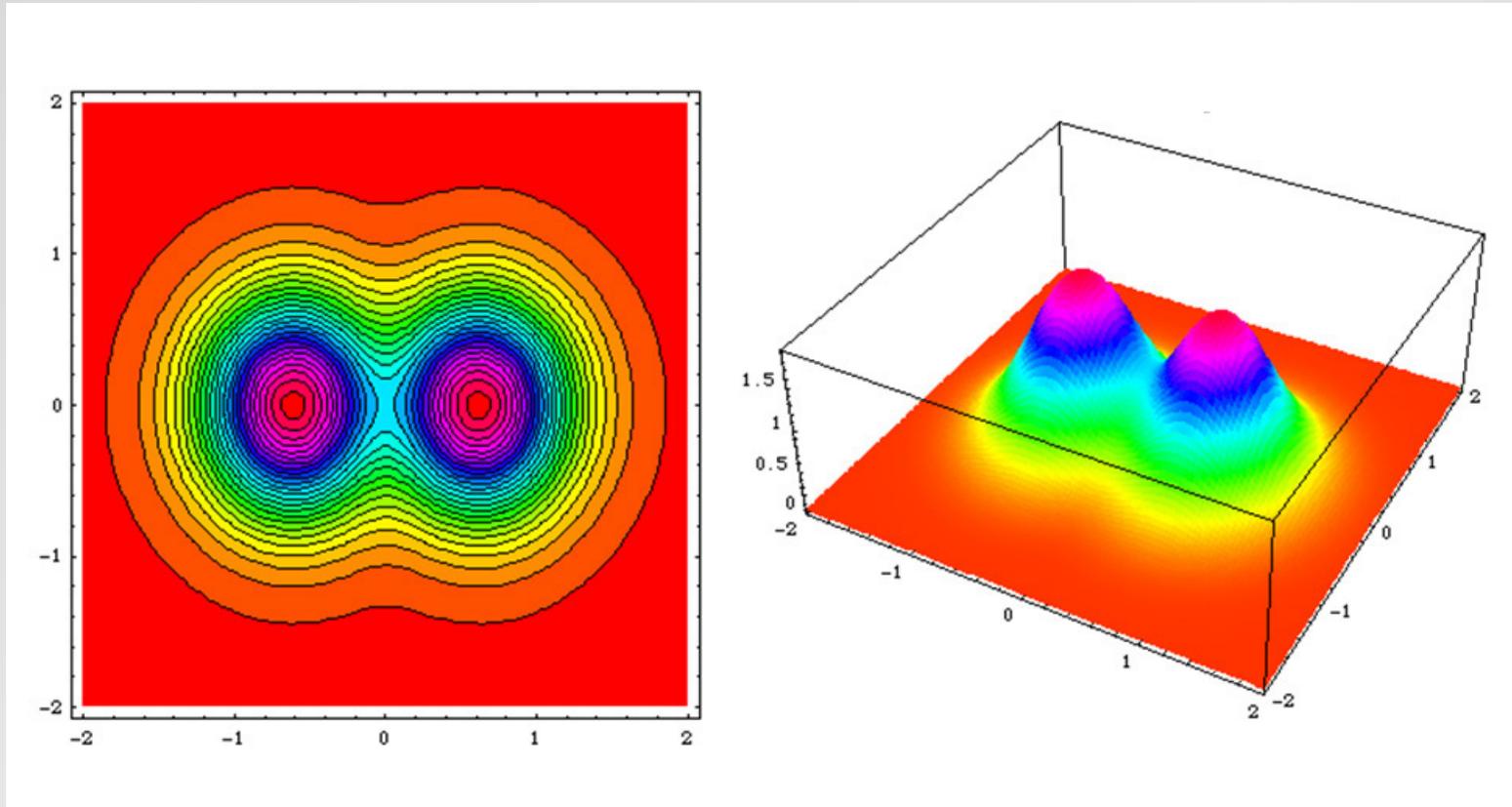
# Preliminary results

planned: add compressor and beam shaper to fiber beam line



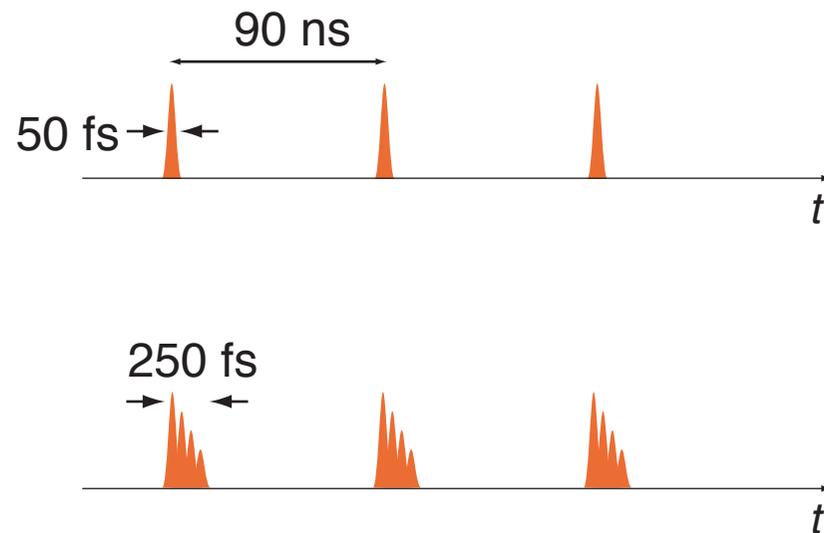
# Preliminary results

focal plane engineering



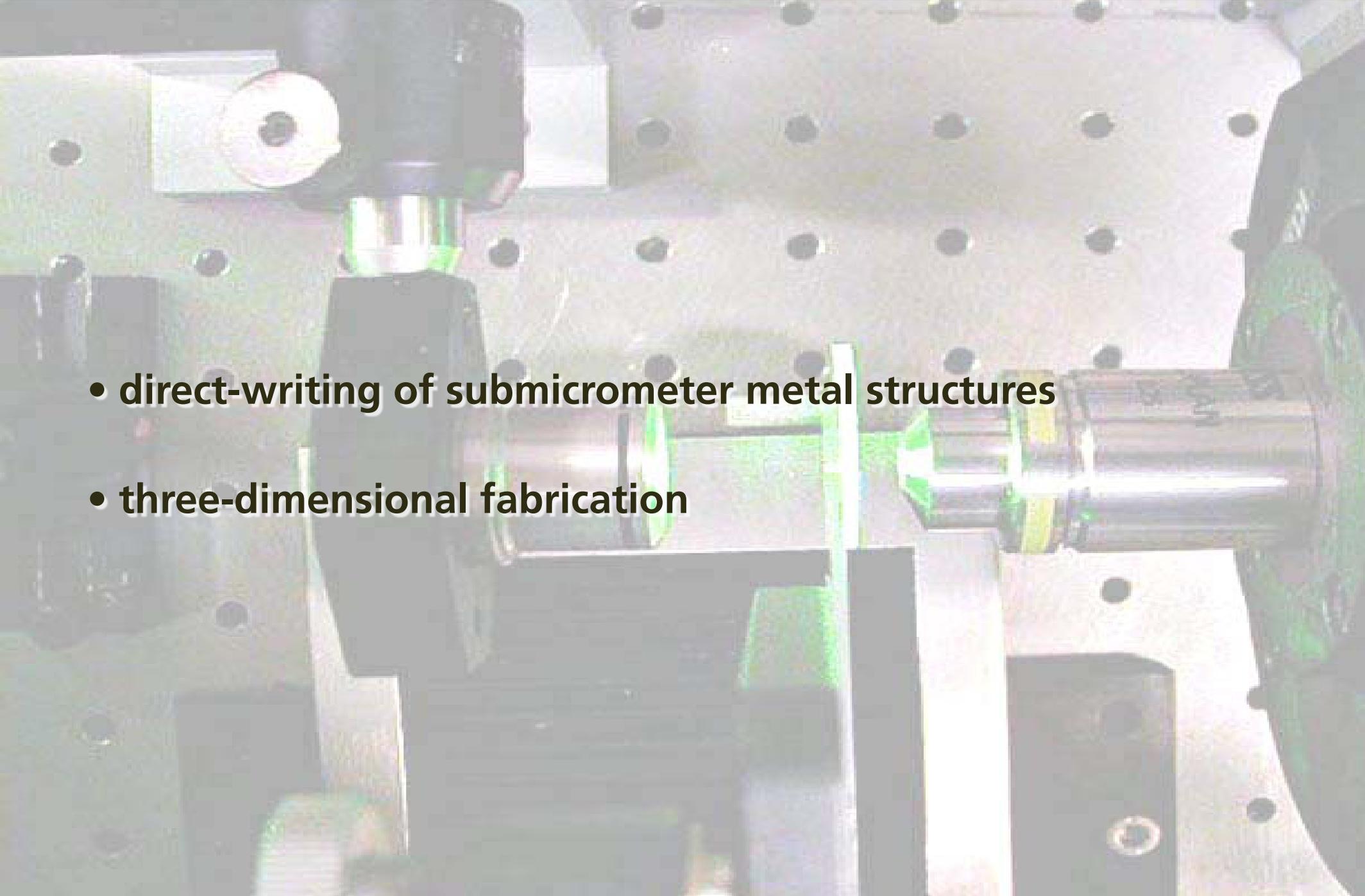
# Preliminary results

## pulse shape engineering



# Summary

- **direct-writing of submicrometer metal structures**
- **three-dimensional fabrication**





**Funding:**

**Air Force Office of Scientific Research  
Fonds Québécois de la Recherche sur la Nature et les Technologies  
Harvard University Center for the Environment**

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