LA-UR-16-27171
Approved for public release; distribution is unlimited.

Title: Diamond field emitter array cathodes and possibilities for employing additive manufacturing for dielectric laser accelerating structures

Author(s): Simakov, Evgenya Ivanovna
Andrews, Heather Lynn
Herman, Matthew Joseph
Hubbard, Kevin Mark
Weis, Eric

Intended for: Presentation at Stanford University

Issued: 2016-09-20

Diamond field emitter array cathodes and possibilities for employing additive manufacturing for dielectric laser accelerating structures

Evgenya I. Simakov, Heather L. Andrews, Matthew J. Herman, Kevin M. Hubbard, and Eric Weis

Los Alamos National Laboratory

Stanford University

September 20, 2016

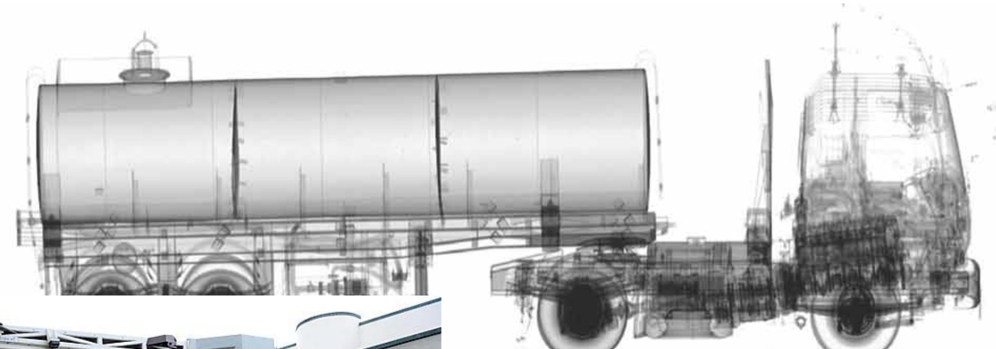
Outline

- Motivation: customers for compact accelerators
- LANL’s technologies for laser acceleration
- DFEA cathodes
- Additive manufacturing of micron-size structures
- Conclusions and plans

Motivation

Customers for compact accelerators

National Security: DARPA, DTRA, NA-22



Basic science: ⇒

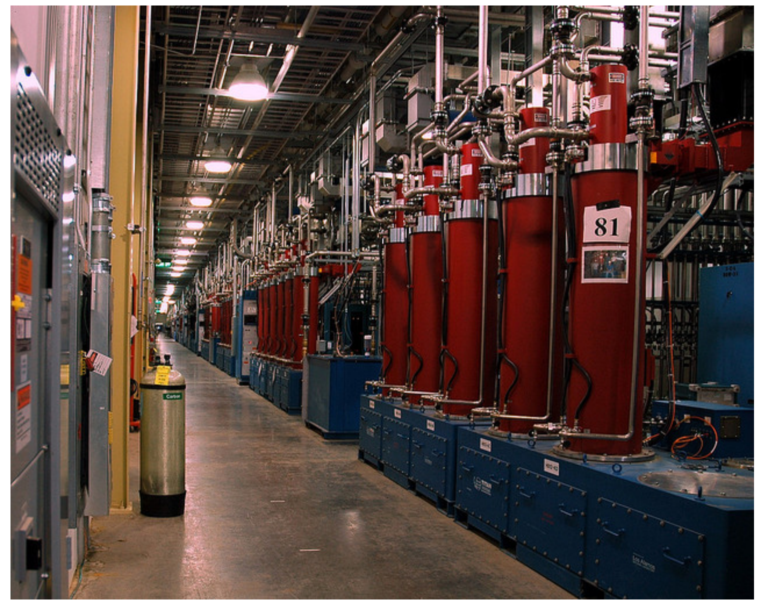
Medicine:

Big problem: accelerators today

Accelerator:

10-30 MV/m

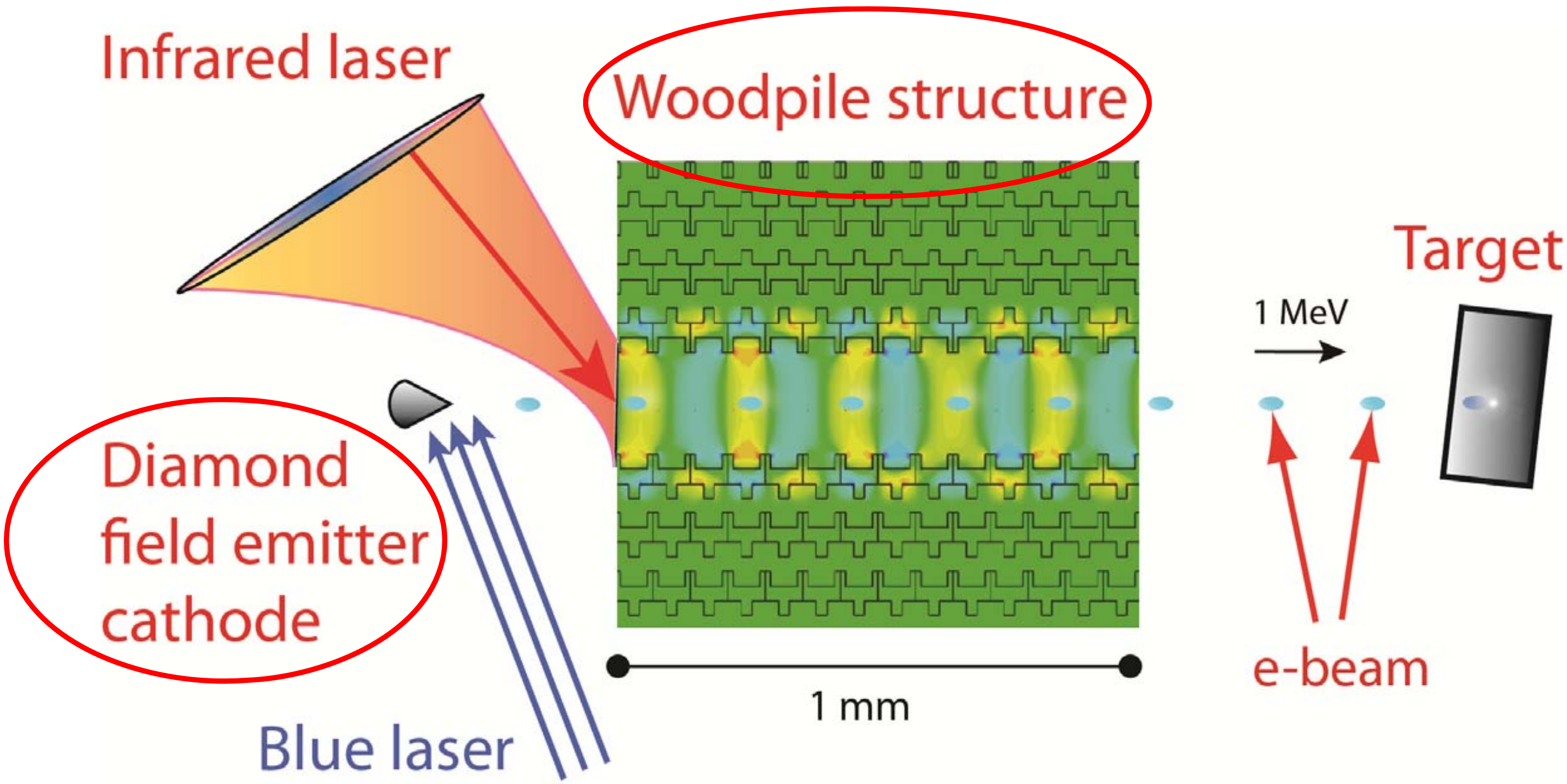
Klystrons:



10 MW each

LANL's technologies

Cathodes and structures for dielectric laser accelerators



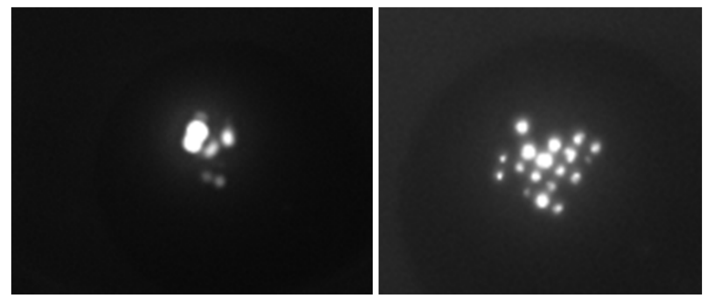
Diamond field emitter array (DFEA) cathodes

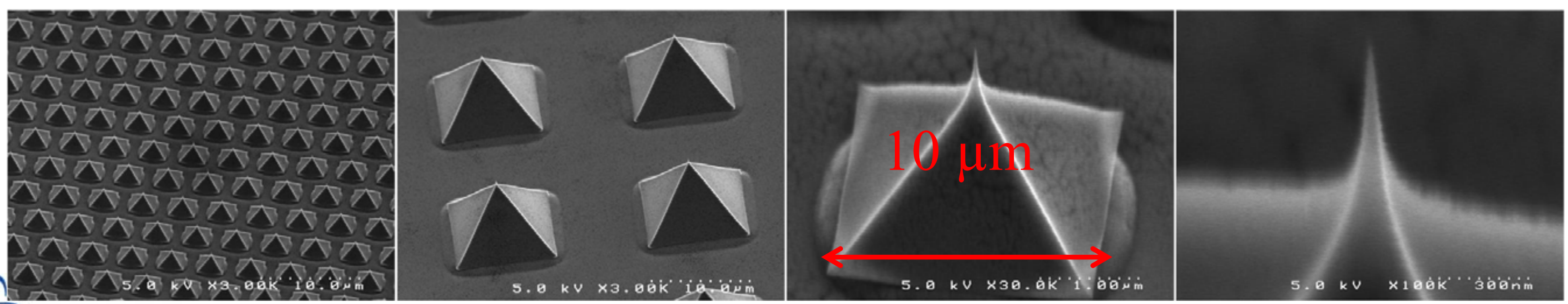
Diamond field emitter arrays

- Exquisitely sharp diamond pyramids.
- Current > 1 A/mm^2.
- Emittance < 1 mm*mrad.
- Photoemission never studied.

Should produce more current with smaller emittance.

We measured ~20 μA currents emitted by single diamond pyramids.





Limits for achievable currents

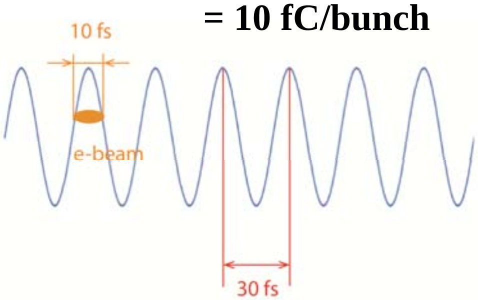
Field emission cathodes	Field emission in DFEAs	Photoemission (space charge)
10 A/cm^2	100 A/cm^2 = 0.1 mA per 10 μm square	$\varepsilon_0 E/\tau = 10^6$ A/cm^2 = 1A per 10 μm square

Will quantum efficiency and laser power limit the current?

Example: 193 nm ultraviolet laser

- Wavelength 193 nm (6.4 eV), energy 200 mJ, pulse length 20 ns.
- Focus down to 5 mm x 5 mm.
- 40 W ($40 \times 6.3 \cdot 10^{18}$ eV/s) in 10μm x 10μm ($4 \cdot 10^{19}$ photons).
- QE is unknown, depends on doping, surface, etc.

1 A peak current = 10 fC/bunch



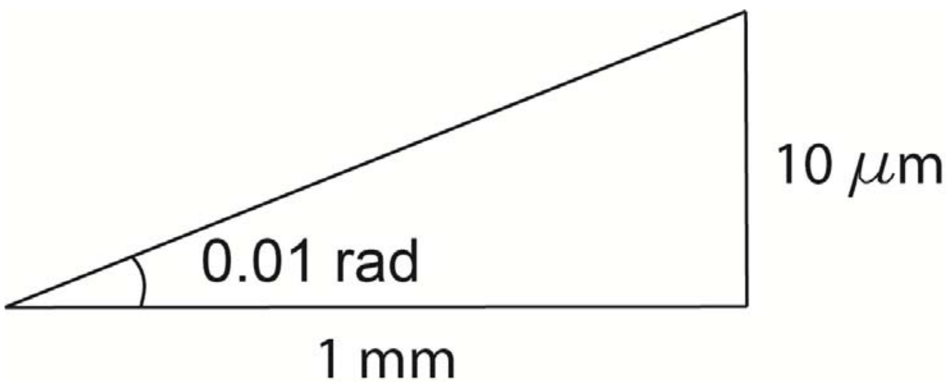
K. Quintero, et al., APL 105, 123103 (2014) reports QE of 10^{-3} for flat surface hydrogen-doped diamond at 254 nm.

- With QE $\sim 10^{-3}$ we get $4 \cdot 10^{16}$ electrons/emitting surface/s

3 mA per 10 μm square

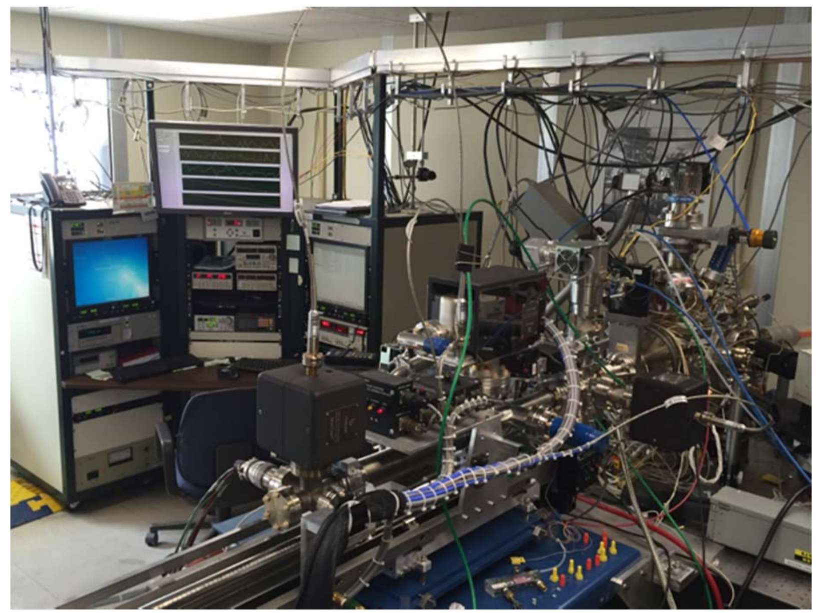
Emittance requirements

Beam emittance: 0.1 mm*mrad = 100 nm
Transverse size: 10 μm
Angular divergence: 10 mrad
Travel distance: 1 mm
Accelerating gradient: 1 GV/m
Total energy: 1 MeV



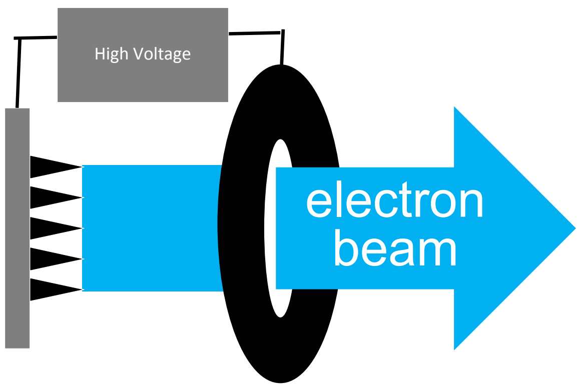
Dedicated cathodes research facility at LANL

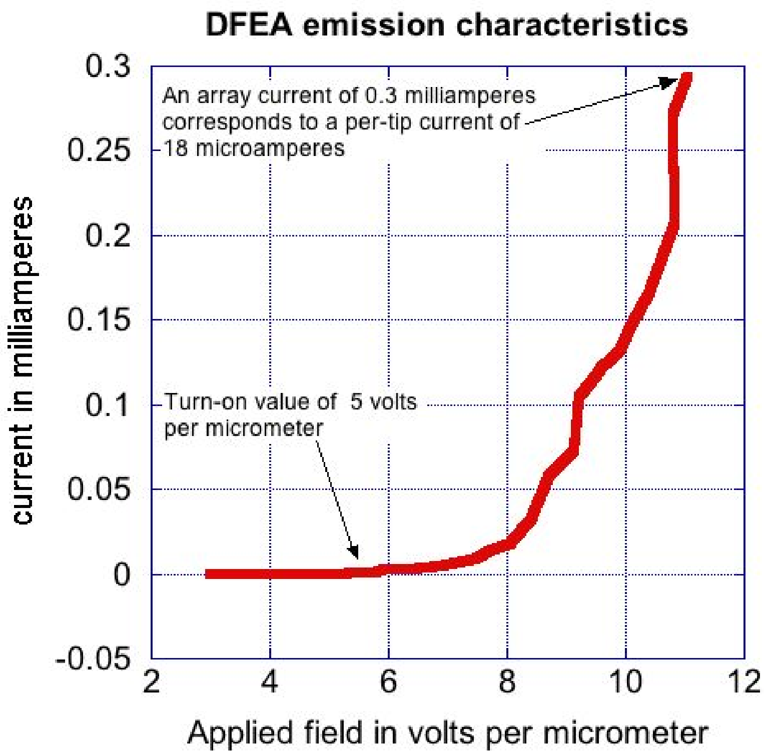
- Dedicated DFEA cathodes testing chamber.
- New emittance measurement test stand with <0.1 mm*mrad resolution built by Nathan Moody.



Some test results in field-emission regime

- Four samples tested in the new chamber in field emission regime.
- Three samples are arrays of large pyramids (25 µm base) with 500 or 1000 µm spacing, one sample has pyramids spaced 4 µm apart.



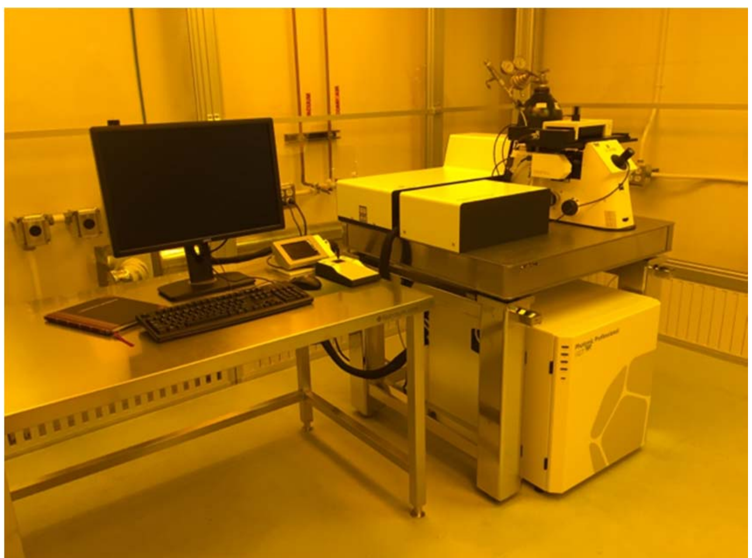


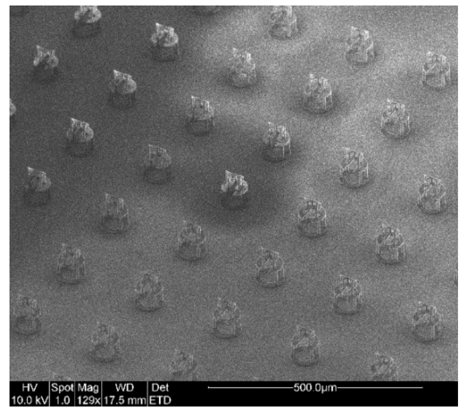
Additive manufacturing of micron-size structures

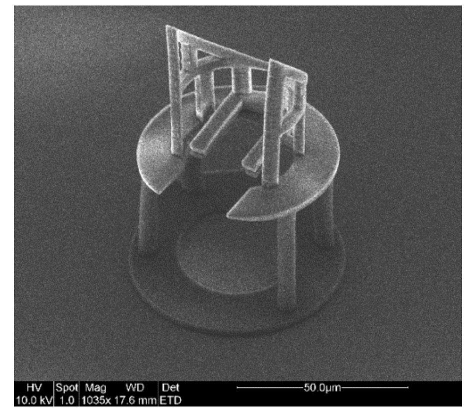
Nanoscribe Professional GT

Installation occurred October 20th - 23rd 2015.

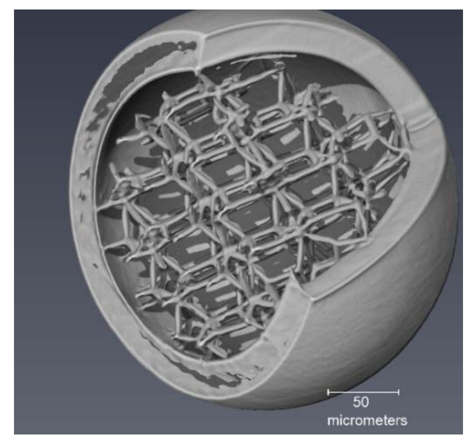
- 3D laser lithography system
- Resolutions down to 100 nm (highest resolution commercially available)
- Print areas as large as 100 x 100 mm
- 2-photon exposure of common positive-tone photoresists





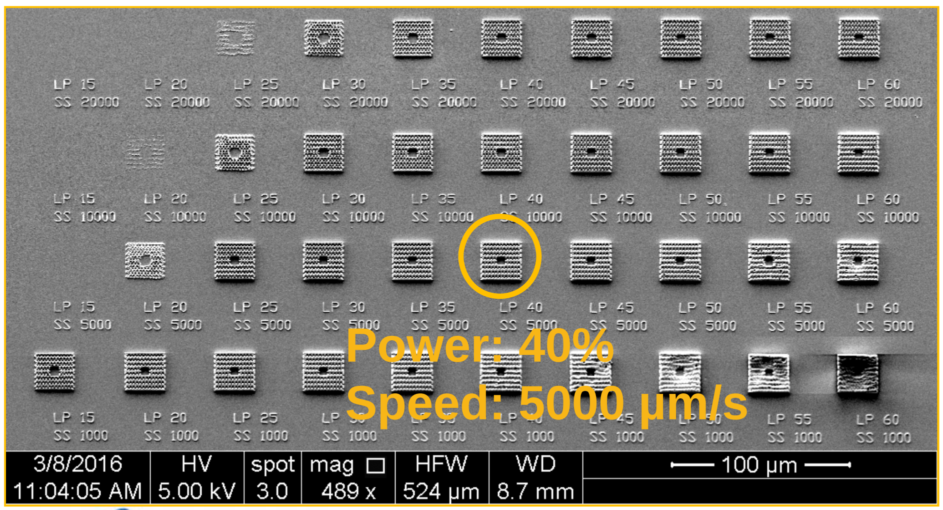


Print of a LANL designed, greatly scaled down, NIF Cepheus mirror physics package holder. Imaged with CT scan.

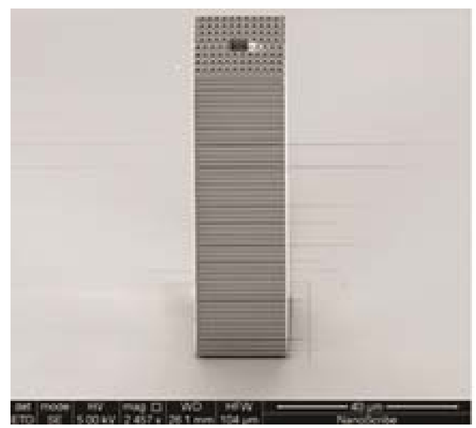


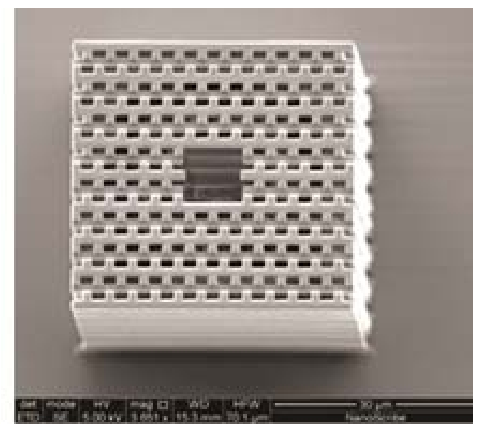
Fabrication of woodpile structures

- Nanoscribe system is perfectly suited to print wood-pile structures on a micron scale.
- ***Work has already started, supported by LDRD Reserve.***
- Resolution: ~100 nm (lateral) x 500 nm (vertical), smallest features below 1 µm.

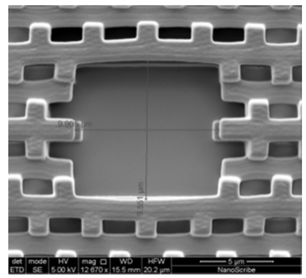
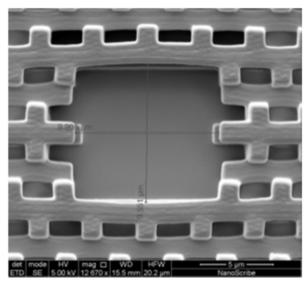
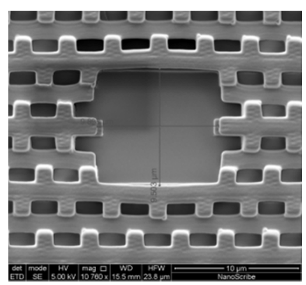


Bulk structures printed with IP-Dip



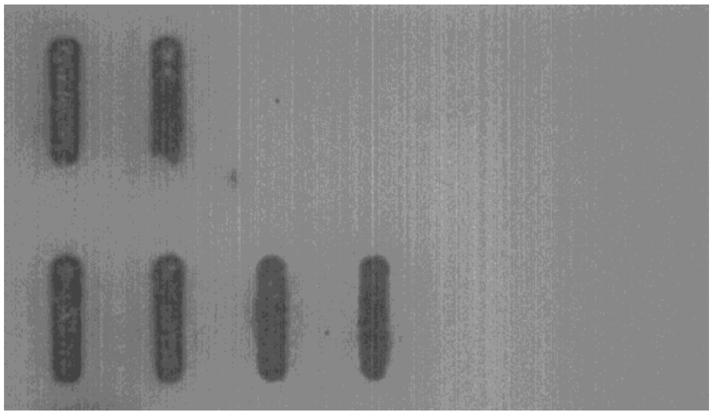


Accuracy studies

Printing Parameters	Measurement Image	Nominal Dimension	Realized Dimension
Power: 35% **Speed: 5000 µm/s**		9.010 µm 9.021 µm	9.905 µm 9.551 µm
Power: 40% **Speed: 5000 µm/s**		9.010 µm 9.021 µm	9.770 µm 9.271 µm
Power: 45% **Speed: 10,000 µm/s**		9.010 µm 9.021 µm	9.898 µm 9.503 µm

3D printing with composite materials

Use Nanoscribe to print a composite material



10% w/w $BaTiO_3$ in Acrylic Resin

150 μm × 30 μm blocks

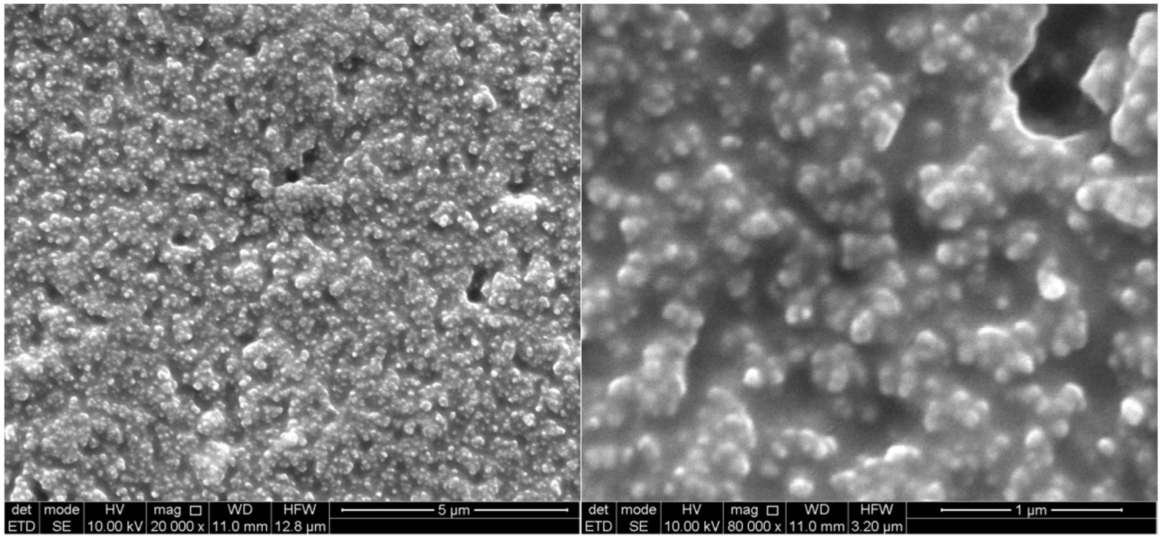
Assess the suitability of printable materials for DLA application

Material	ε′ (1000 cm^{-1})	ε″ (1000 cm^{-1})	ε′ (2000 cm^{-1})	ε″ (2000 cm^{-1})
Acrylic	2.2	0.1	2.1	<0.01
$BaTiO_3$ Crystal	2.79	0.15	4.75	0.05
Composite	2.3	0.4	3	<0.1

Measuring dielectric properties of new materials

We prepared some test coupons to be taken to CINT-Sandia and analyzed with Mid-IR ellipsometry.

SEM Micrographs of BTO-VeroClear Composite

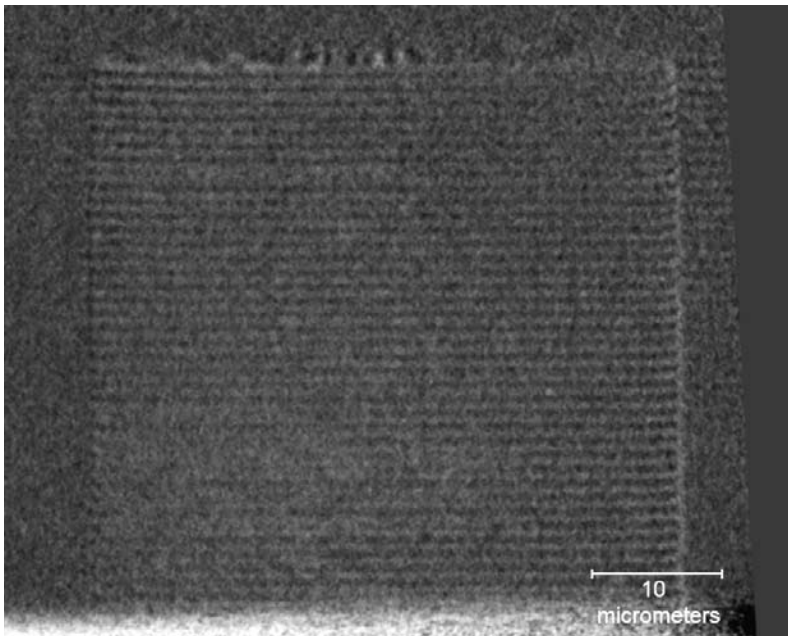


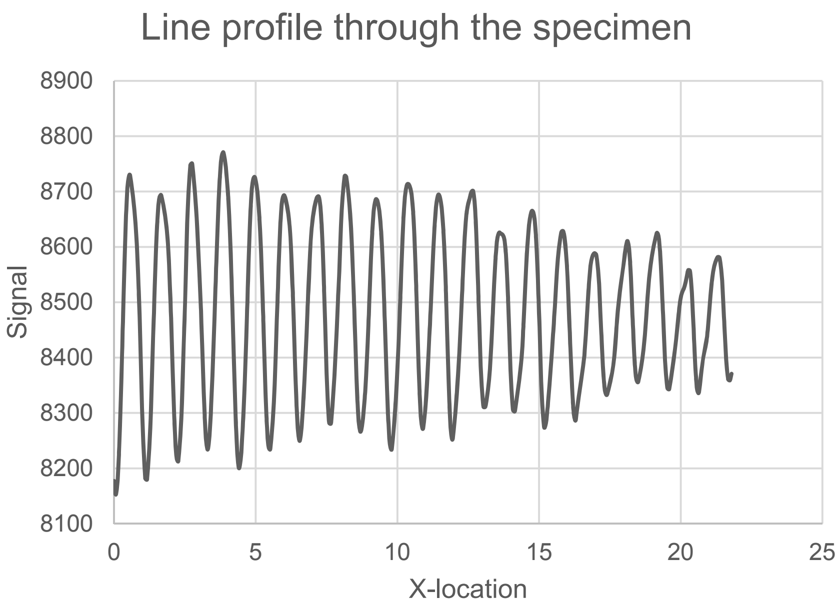
Photograph of a test coupon with reflected light source

Structural Fidelity Assessment

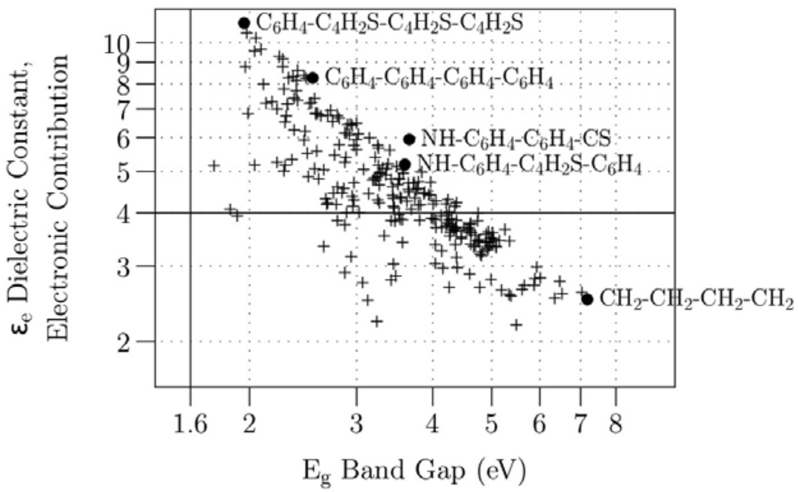
Structural fidelity was assessed with micro-CT, 1% triphenyl bismuth was added for contrast.

Expected spacings 1 μm, measured spacings 1.08 μm.



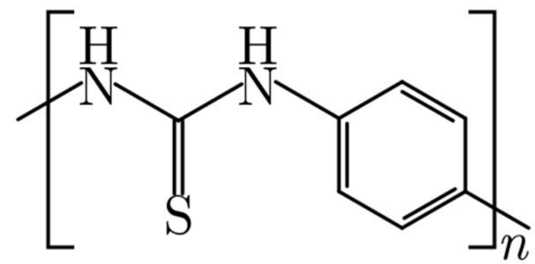


Materials development strategy



V. Sharma *et al.*, Rational design of all organic polymer dielectrics. *Nat. Commun.* **5**, 4845 (2014).

Structural Motif Example



Down-Selection → Synthesis → Determine ε′, ε″ →

Printing & Imaging

Conclusions and plans

Conclusions and future plans

- LANL is funded to do dielectric accelerator research starting in FY17.
- Preliminary studied identified DFEA cathodes as promising sources for DLAs: high beam current and small emittance.
- Additive manufacturing with Nanoscribe Professional GT can produce structures with the right scale features for a DLA operating at micron wavelengths:
  - Fabrication tolerances need to be studied.
  - DLAs require new materials.
- We start in October and welcome collaborations!
  - DLA experiment with a beam produced by the DFEA cathode with field emission.
  - Demonstration of photoemission from DFEAs.
  - New structures to print and test.