Multi-material glass AM and possibilities for TO of optical systems

Rebecca Dylla-Spears
dyllaspears1@llnl.gov, 925-422-1700

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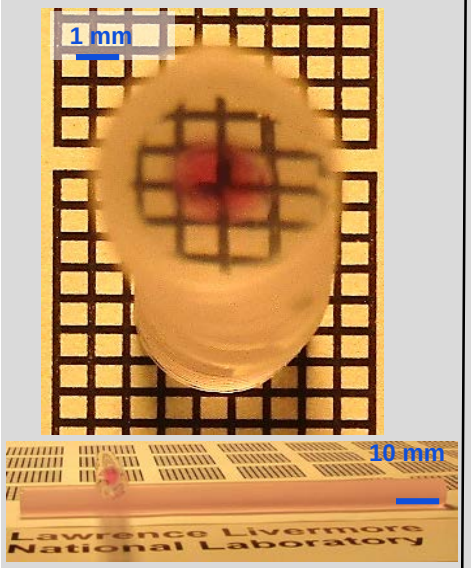
Lawrence Livermore National Laboratory

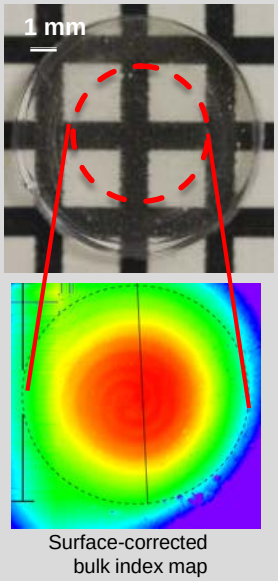
LLNL has invested heavily in advanced manufacturing of optics to enable future missions

Bulk compositional gradients



Laser rod with engineered gain profile (YAG)

10-cm core-clad rod
First light



Surface-corrected bulk index map

Glass optic with gradient refractive index (GRIN)

1-cm GRIN lens
Optical index homogeneity

I. Jones *et al*., *Opt. Mater.* 75: 19-25, 2018.

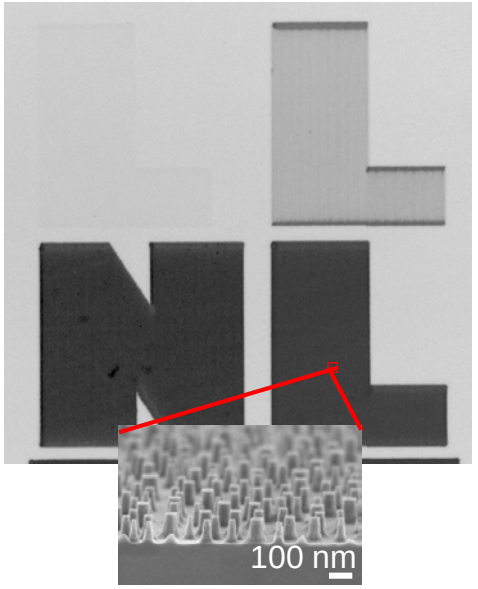
Contact:
Zach Seeley, LLNL
seeley7@llnl.gov

Structural gradients

Mirror and support with gradient stiffness

7-cm flat mirror
Conventionally polishable

Surface gradients



Metasurface optics with tunable reflectivity

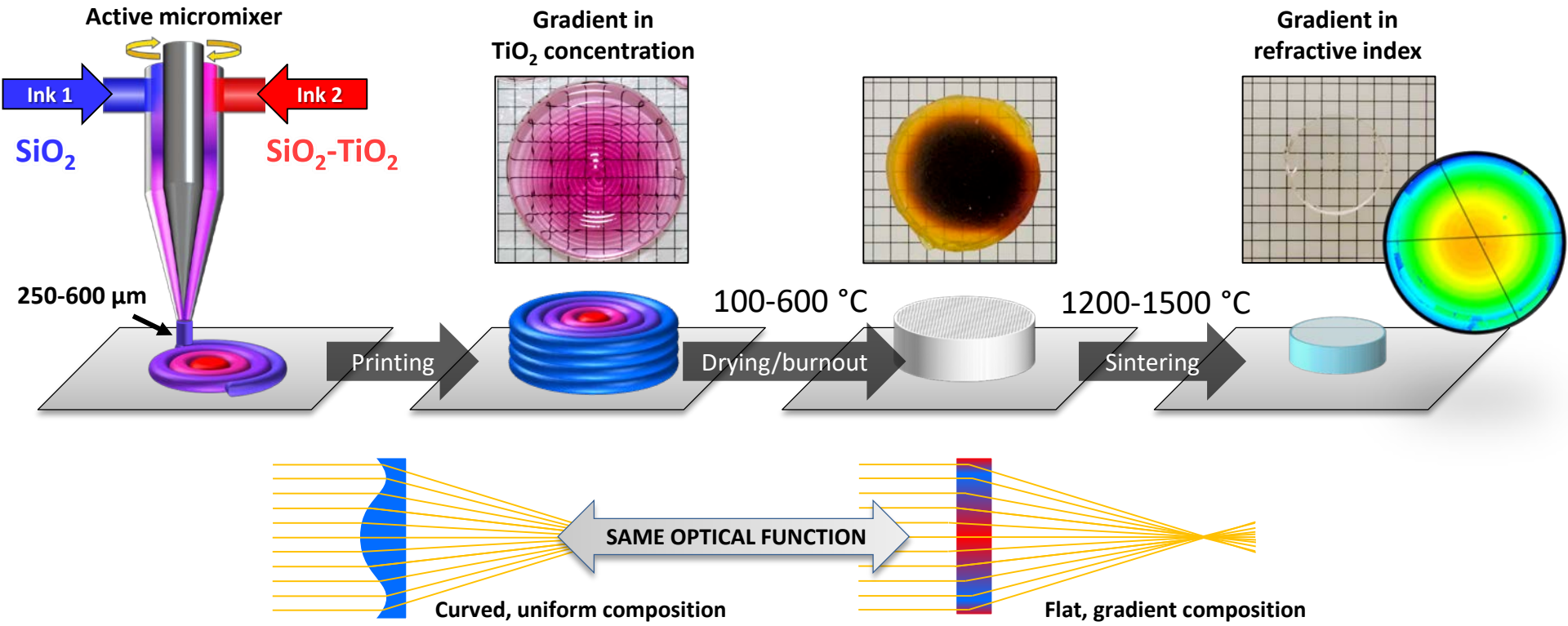
2-cm durable AR meta-surfaces in glass by scalable process

J. Yoo *et al.,* ACS Appl. Mater. Interfaces 11, 22684-22691 (2019)

Contact:
Eyal Feigenbaum, LLNL
feigenbaum1@llnl.gov

YAG = Yttrium Aluminum Garnet
DIW = Direct Ink Writing

Compositional gradients in glass are achieved using direct ink writing (DIW) of SiO_2 slurries with active mixing

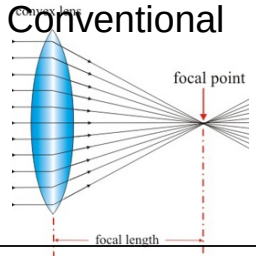
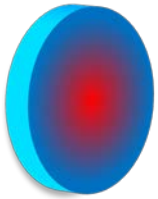
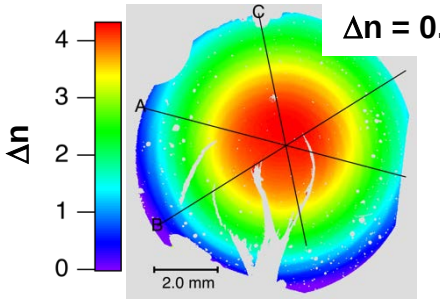
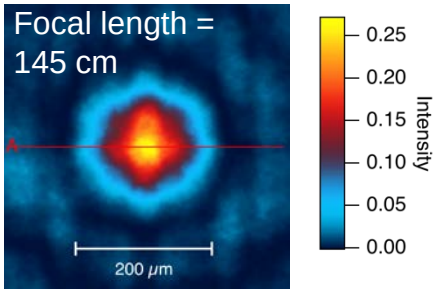
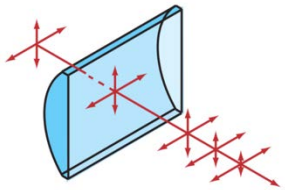
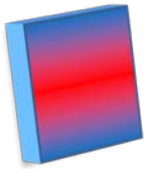
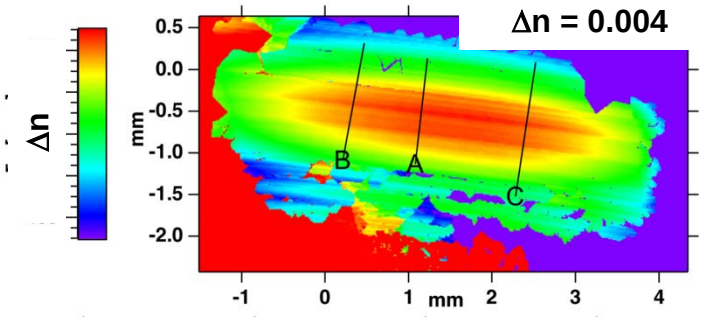
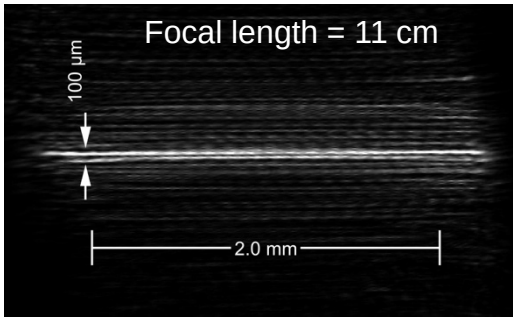
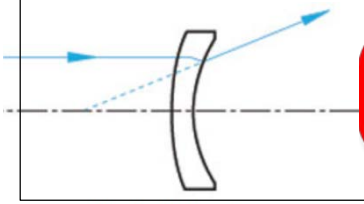
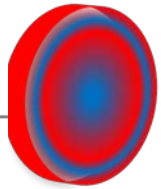
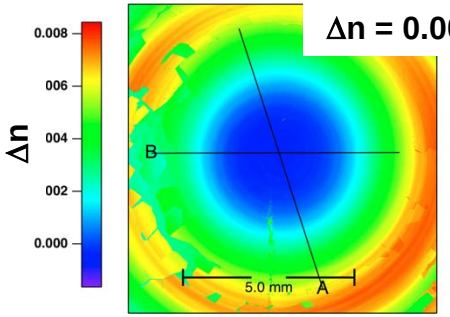
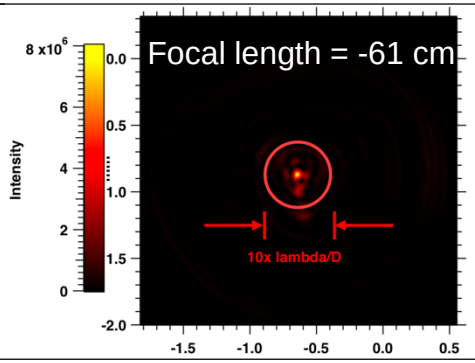


Nguyen, D.T. *et al.*, *Adv. Mater.* **2017,** *29* (26), 1701181

Dudukovic, N. A. *et al.*, *ACS Applied Nano Mater.* **2018,** *1* (8), 4038-4044.

Material properties can be tuned by adjusting relative flow rates of different ink compositions

Using TiO_2-doped SiO_2 inks, we have produced flat GRIN glass optics with three different functionalities; max Δn of ~0.01

Lens Type	Refractive Index Maps	Focus
Spherical Conventional  GRIN 	 **Δn = 0.004**	
Cylindrical Conventional  GRIN 	 **Δn = 0.004**	
Aspheric, Negative Conventional  GRIN 	 **Δn = 0.008**	

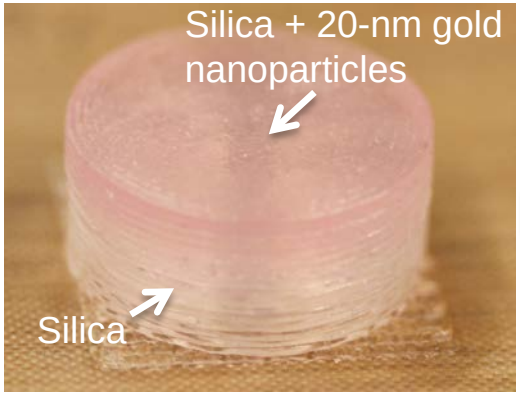
DIW also enables material switching to yield regions of glass with distinct material properties

Printed low density form

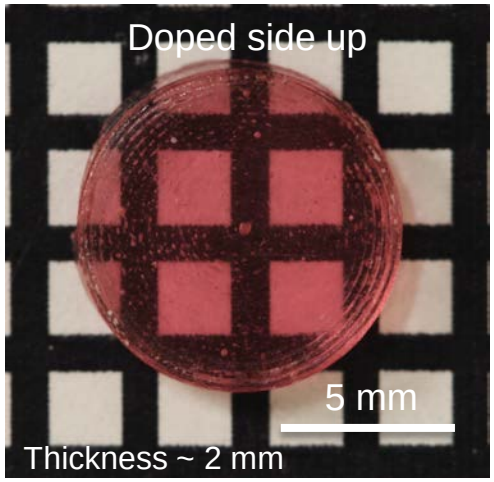
Consolidated glass

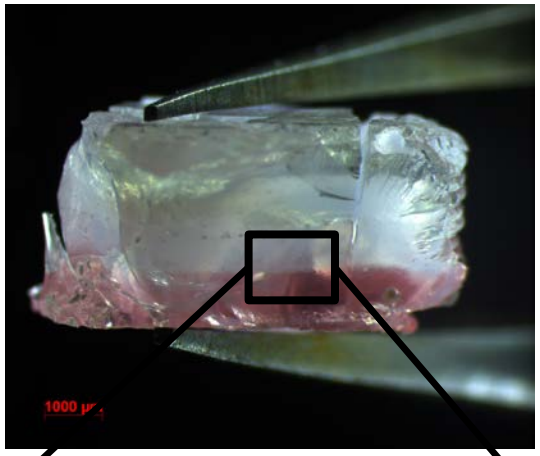
Cross section of step-graded glass

Axial step

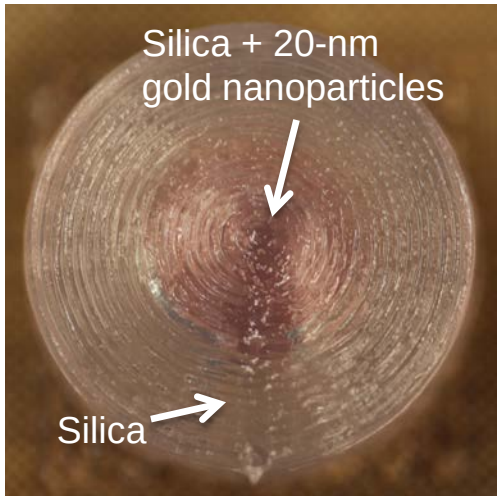


Dry, heat treat

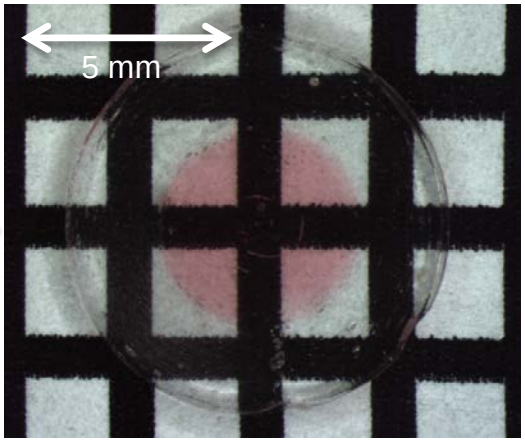


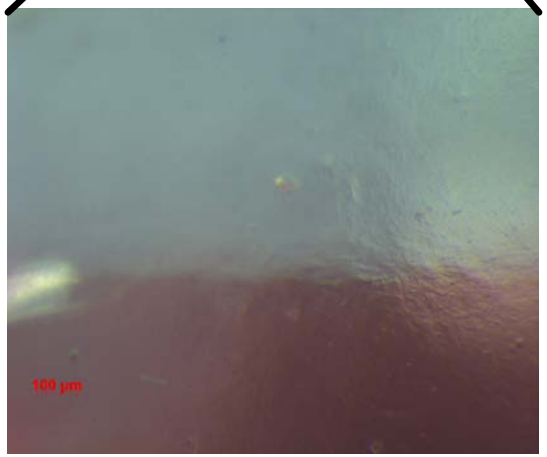


Radial step



Dry, heat treat



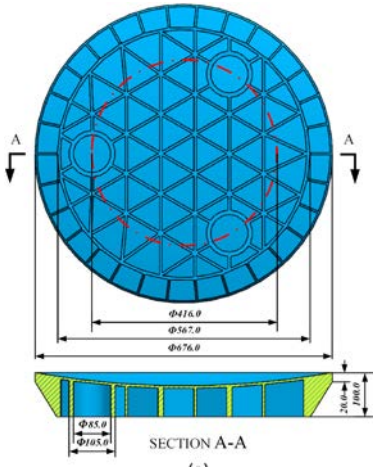


Topology optimization combined with AM can be used to impact performance of individual optical elements

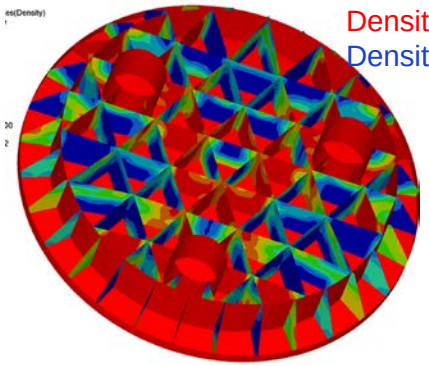
Mounts and supports

Lightweighting

Original design



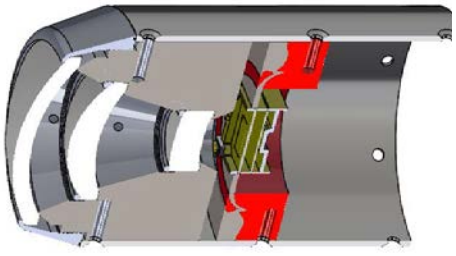
TO design



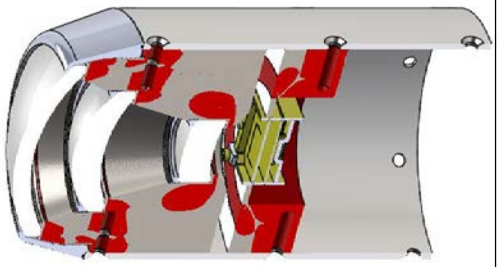
G.Liu, L. Guo, X. Wang, Q. Wu
Opt. Eng. 57(7), 075101 (2018),

Athermalization

Original design



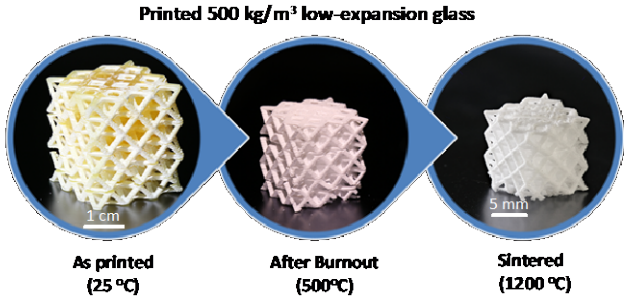
TO design



Metal
Polymer

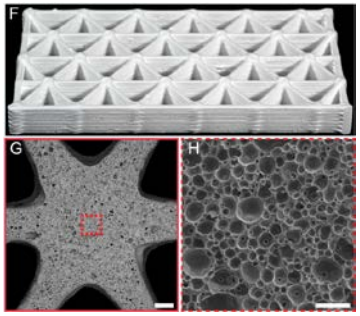
K.R. Bryant, D. Hayduke
Proc. SPIE 10627, Advanced Optics for Defense Applications: UV through LWIR III, 1062705 (8 May 2018);

Architected glass materials



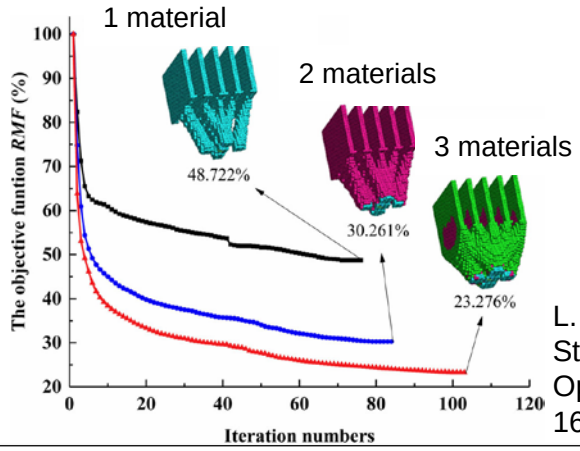
Dylla-Spears, LLNL

Architected cellular ceramics



J.A. Lewis, Harvard
J.T. Muth et al., PNAS, 2017

Thermal management



L. Wang et al., Struct. Multidiscipl. Optim. 59: 1599–1620, 2019

TO = Topology Optimized

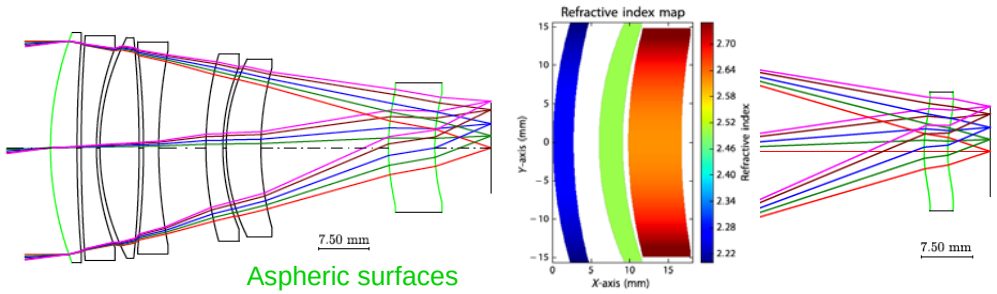
Topology optimization combined with AM can be used to impact performance of individual optical elements

Optics

Bulk material & surface co-design

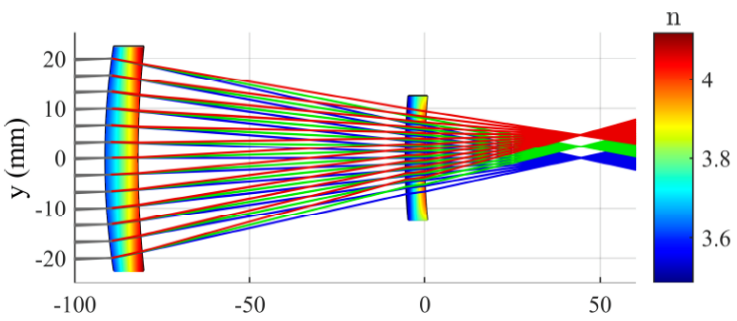
Athermal, multispectral, radial GRIN lenses

Conventional design | **Multispectral, GRIN design**



A. Boyd, Optical Engineering 57(8), 085103, 2018.

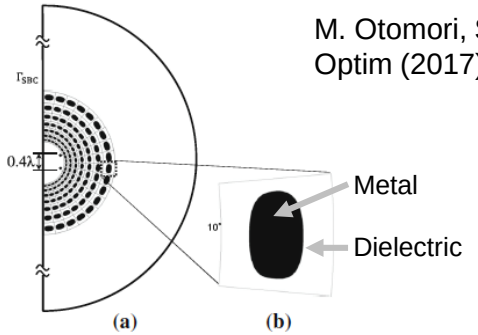
GRIN lenses replacing conventional doublets



J. Nagar et al., Optics Exp. 24(9), 9339, 2016.

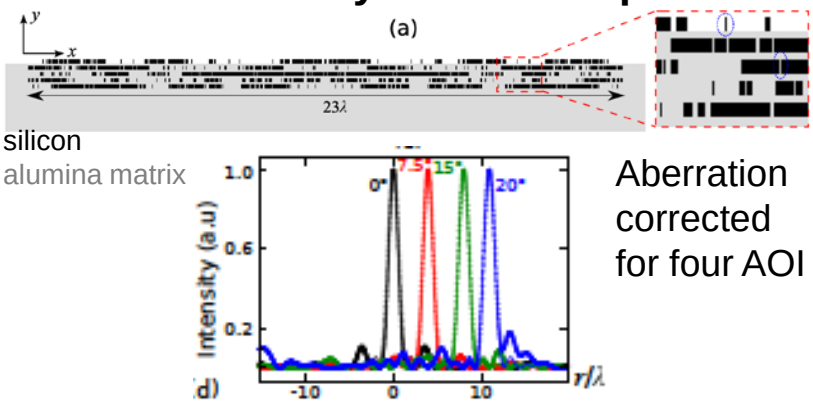
Metasurface design

TO Hyperbolic metasurface microlens



M. Otomori, Struct Multidisc Optim (2017) 55:913–923

TO Multi-layered meta-optics



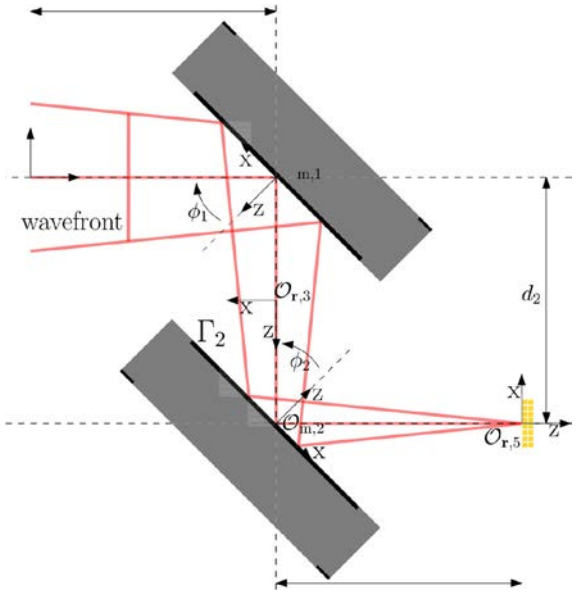
Aberration corrected for four AOI

Z. Lin, Phys. Rev. Applied 9, 044030 – Published 20 April 2018

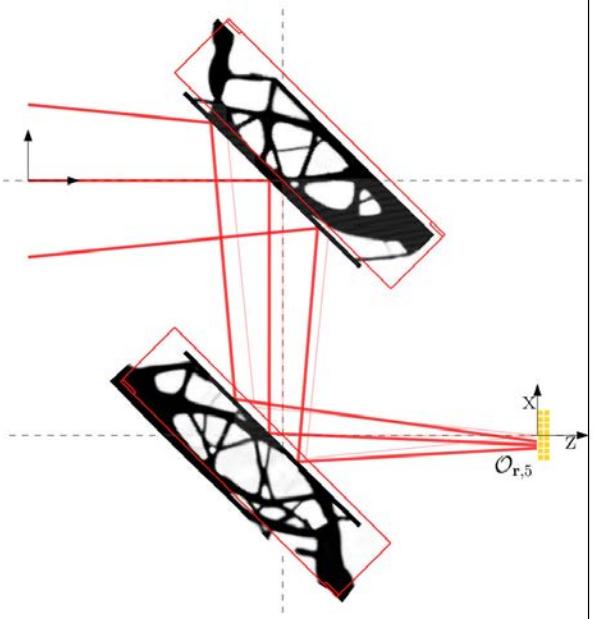
GRIN = Gradient Index
TO = Topology Optimized
AOI = Angle of Incidence

Topology optimization can be used to impact performance of the optomechanical system

Problem

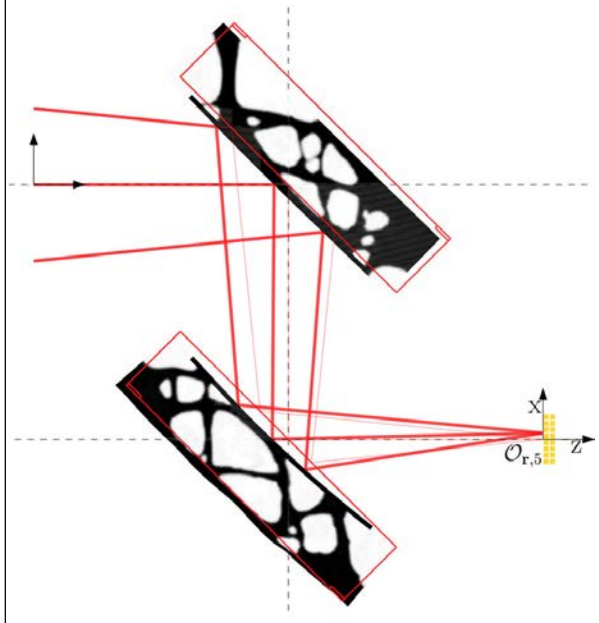


Uncoupled System



~ 13x diffraction-limited spot

Coupled System

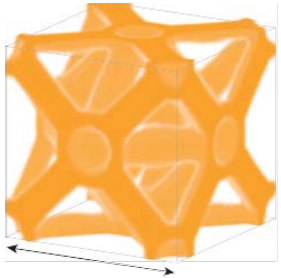


Diffraction-limited spot

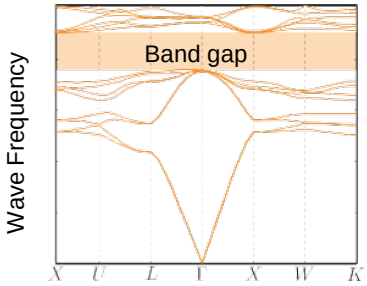
M. Langelaar, Delft University of Technology
S. Koppen et al., Structural and Multidisciplinary Optimization (2018) 58:885–901

System level optomechanical system optimization can be further enhanced by including meta materials and multiple materials

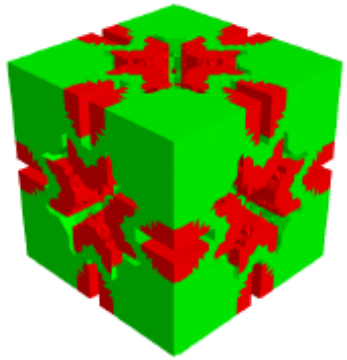
- Optimal band gap materials serve as perfect reflectors
- Light weight supports enable fuel savings
- Mounts with thermally insensitive materials ensure accuracy



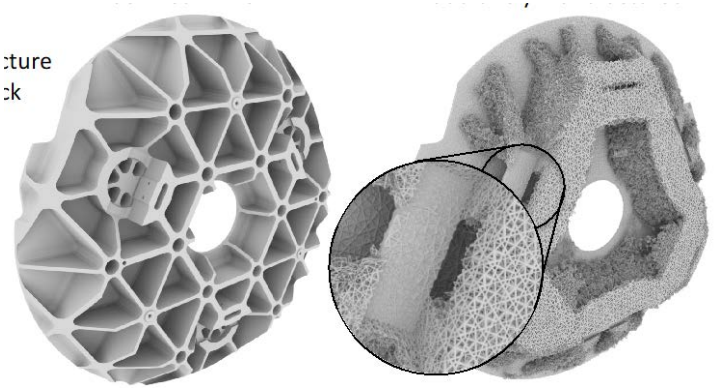
Perfect reflectivity mirror material



Contact:
Dan Tortorelli, LLNL
tortorelli2@llnl.gov



Zero CTE mount material



Equal stiffness support with 50% weight savings

Challenges or barriers to implementation

- Integration of optical performance tools with TO tools
- Broadening the range of 3d printable materials
- More exploration of integration of disparate materials
- Scale-up still needed in a variety of materials/multi-material systems