Additively Manufactured Freeform Gradient Index Optics

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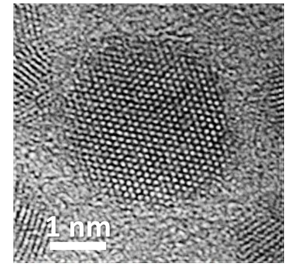
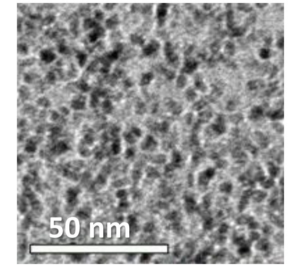
Volumetric Index of Refraction Gradient Optics (VIRGO)

Freeform Gradient Inks Optics

Optically-engineered Nanocomposite Feedstock

- Nanoparticle fillers used to tune optical index and dispersion
- Sub-10-nm unaggregated particles avoid scatter
- Nanocomposites strong, hard, and durable
- No birefringence and low dn/dT



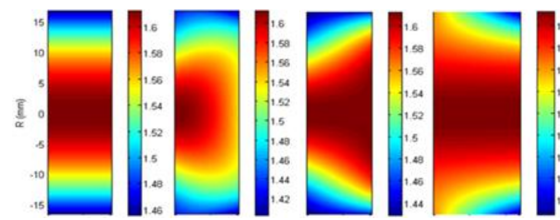


InkJet Print Additive Manufacturing (AM)

- Low cost on-demand fabrication – 24 hour turn
- Micron-scale drop placement, with sub-λ gradient resolution
- Local mixing and diffusion creates smooth gradients
- Local curing for process control and stress relief

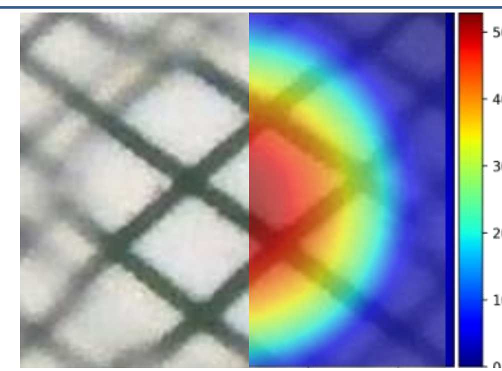
Design Tools For Added Design Degrees of Freedom

- Plug-in tools for Zemax and Code-V
- Custom stochastic optimizers with multi-metric solutions
- Accommodate On-axis, off-axis, and freeform gradients



Metrology

- Digital Holographic Microscope (DHM)
- Perkin Elmer Lambda 19 Spectrophotometer
- BYK Gardner Haze meter
- Zygo Zescope Profilometer
- Atago NAR-1T Abbe Refractometer

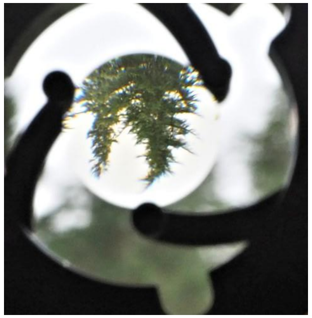


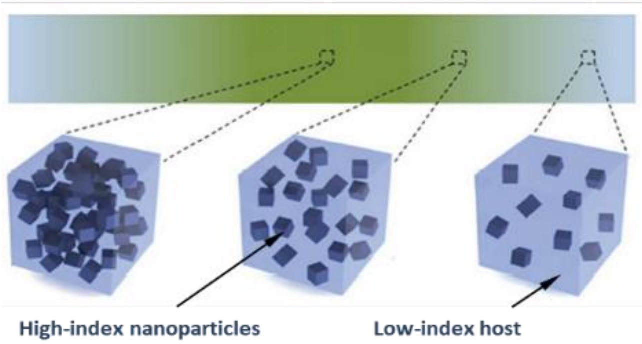
Volumetric Index of Refraction Gradient Optics (VIRGO)

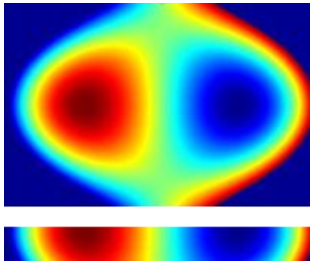
VADIENTOPTICS

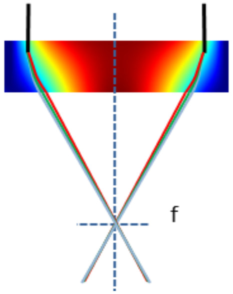
Additive Manufactured Nanocomposite GRIN Optics

- **Nanofiller material type and density determines local refractive index -** n_{λ}
- **Inkjet print deposition, mixing, and diffusion creates refractive index gradients -** $\Delta n_{\lambda} / \Delta(x,y,z)$
- **Optical index gradients *sculpt* light within an optical volume :**
    - provide *optical power*,
    - compensate *geometric aberrations*, &
    - implement *complex optical functions* used to manipulate wavefronts
- **Ternary, quaternery, etc. material compositions**
    - compensate for chromatic aberrations
    - control (partial) dispersion
- **Added degrees of freedom improve optical performance and reduces lens count**
- **Integrated pinholes, aperture stops, baffling, fiducial marks, alignment features, and mechanical mounts**

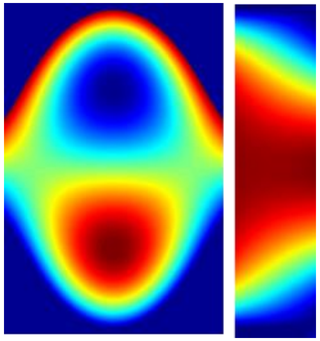




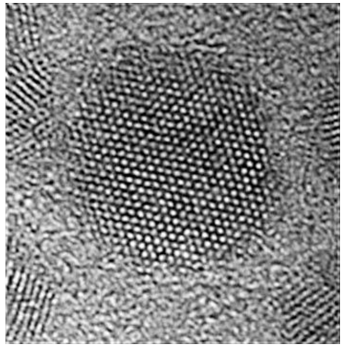




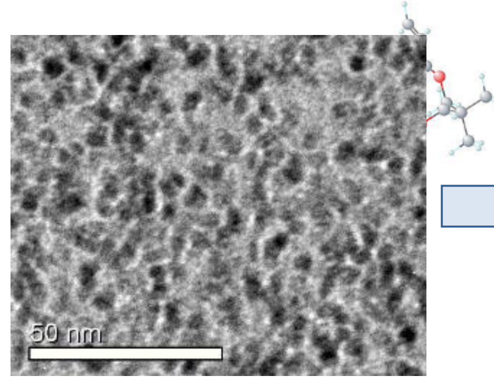
Additive Manufacture of Freeform GRIN Optics



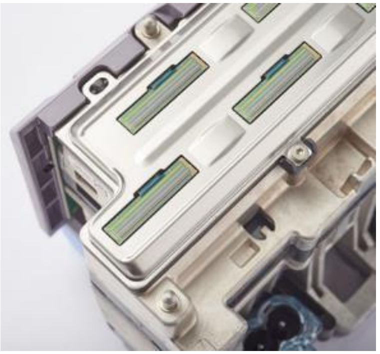
Freeform GRIN Design



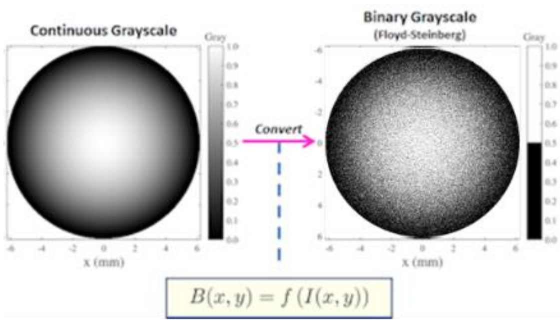
On-demand Nanoparticle Filler Synthesis



On-demand Nanocomposite Ink Formulation

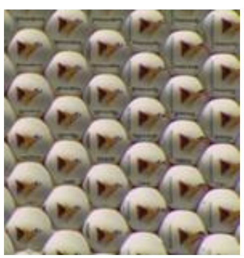


Print Head Load

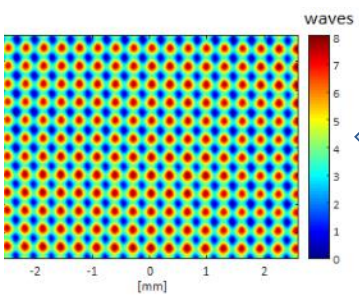


Multi-level Print Diffusion Masks

High-throughput Inkjet Fabrication



3D & Freeform GRIN Optics

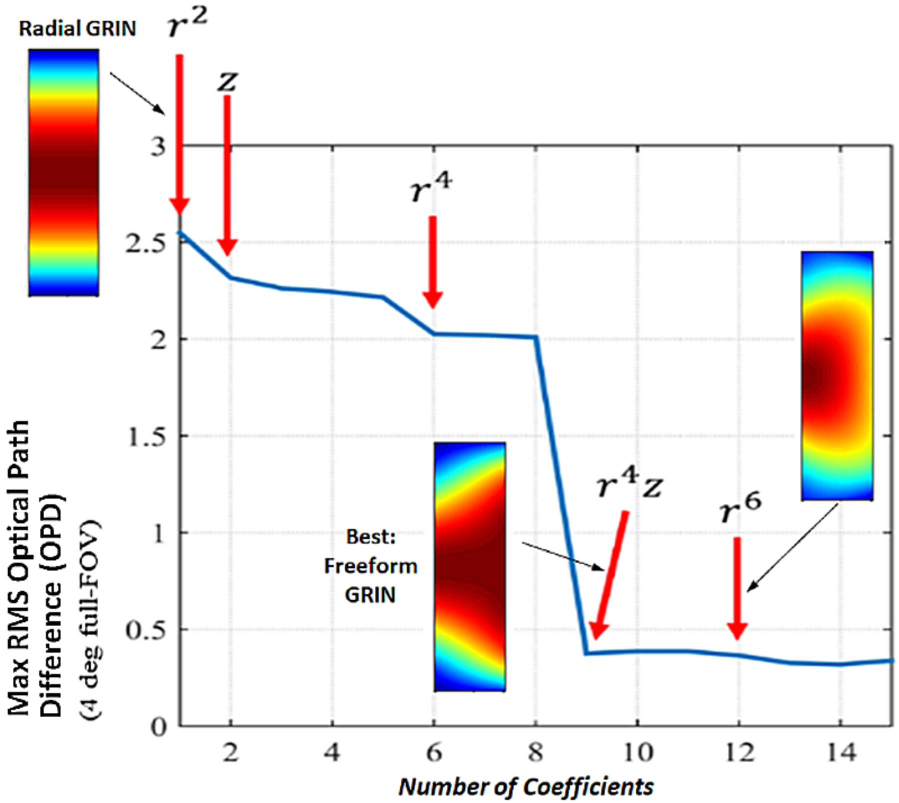


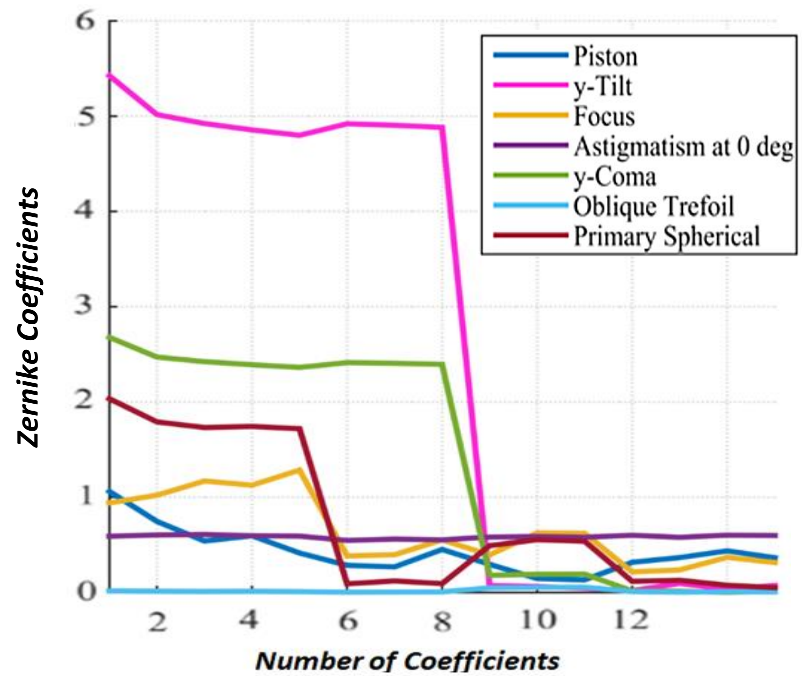
Metrology

- **24-hour design and build cycle time**

VIRGO Increases Design Degrees of Freedom

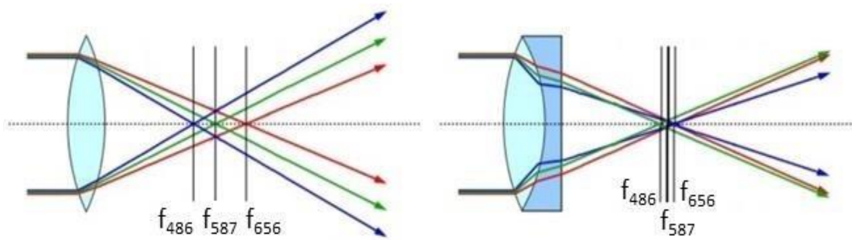
GRIN Equation: $n(x,y,z) = \boldsymbol{n_0} + \Delta\boldsymbol{n}(\boldsymbol{r_2}r^2 + \boldsymbol{r_4}r^4 + \boldsymbol{r_6}r^6 + \boldsymbol{z_1}z + \boldsymbol{z_2}z^2 + \boldsymbol{r_2}\boldsymbol{z_1}r^2z + \boldsymbol{r_2}\boldsymbol{z_2}r^2z^2 \ldots)$



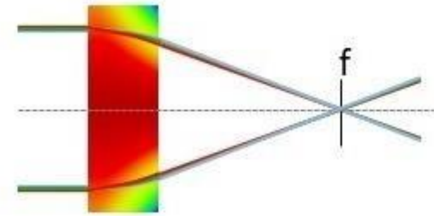


- **Radial gradients provide power, especially for wide field of view optics**
- **Axial gradients replace aspheric surfaces and correct Siedel aberrations**
- **Higher order cross terms (r, Φ, and z) reduce optical aberrations (coma, tilt, spherical, etc)**

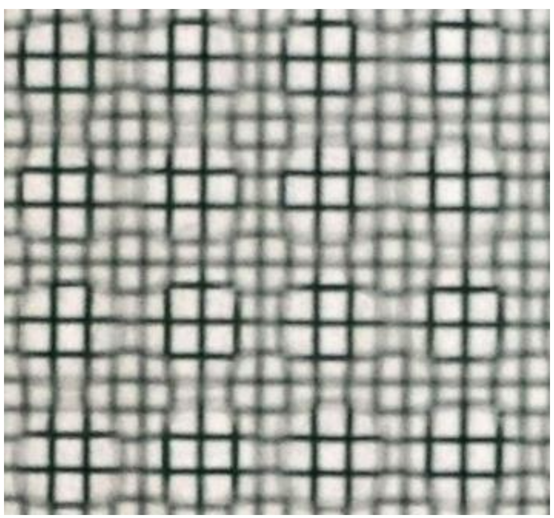
Chromatic Aberration Correction using VIRGO



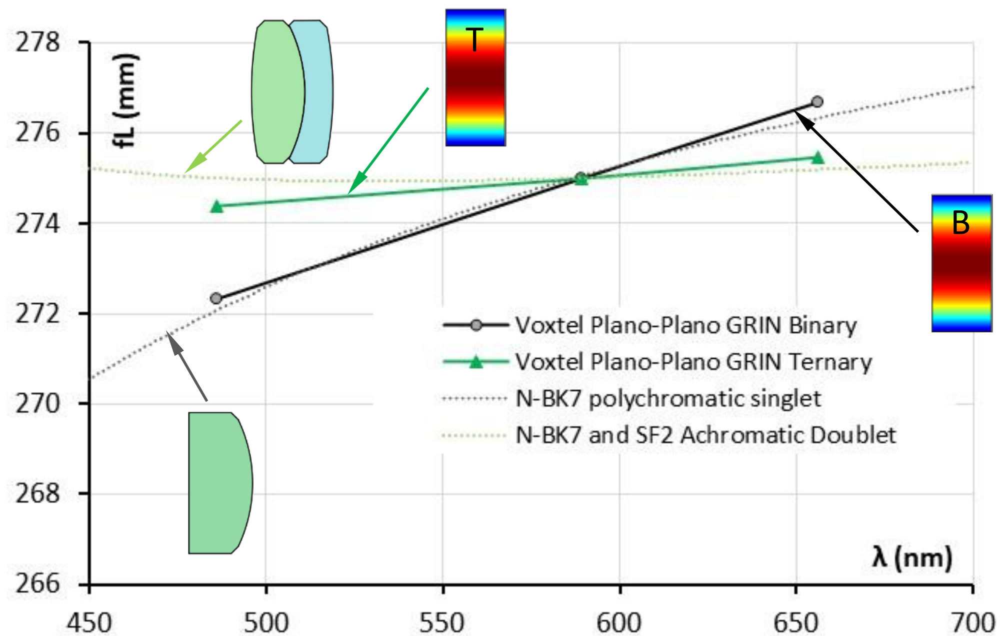
Conventional Optic Singlet (left) and Doublet (right) showing axial chromatic Aberrations



3D GRIN with "Abbe compensated" three material composition



Planar, Radial 2D GRIN lenses made with binary ink (uncompensated) and ternary (Abbe-Compensated) ink



Spectral Compensation: measured focal length variations with binary (B) and ternary (T) nanocomposites, showing achromatic GRIN lens

Scalable, On-demand
Inkjet print Additive Manufacturing

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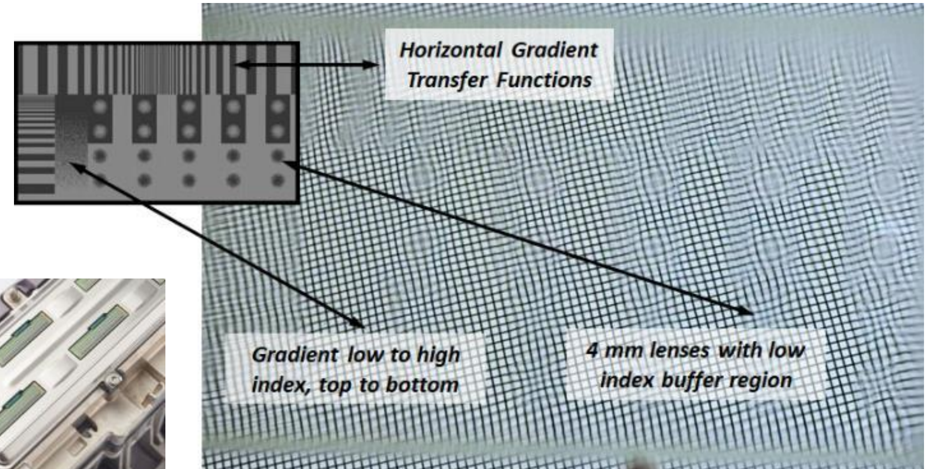
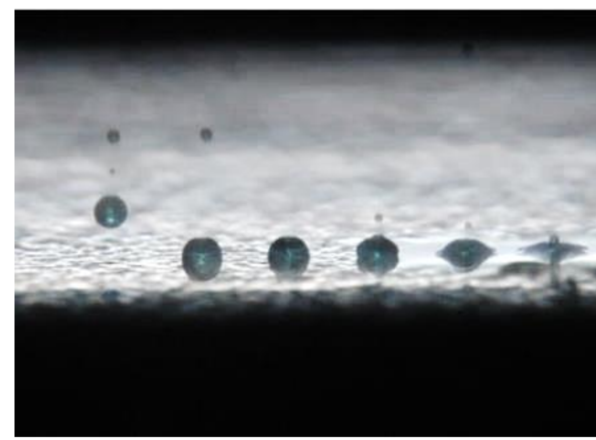
Additive Manufacturing Platform
(Medium-scale Capacity)

Multi-nozzle Printhead



Process Control Pattern

- **VIRGO (Medium-capacity) Production Printers**
  - 6 optical inks fed simultaneously
  - 140M voxels/s (3.5 cc/s) deposition rate
  - 1-m x 1.5-m x 60-mm build volume
  - Designed for continuous (roll-to-roll) feed
- **Capable of 100 optics (25-mm dia. x 4-mm) per hour**
- **Scalable by increasing no. printers or no. print heads (fL to pL)**
- **Approach leverages $Bs of investment and service support offered by commercial print industry**



Droplet monitoring system

VIRGO Free-form GRIN printed optic examples

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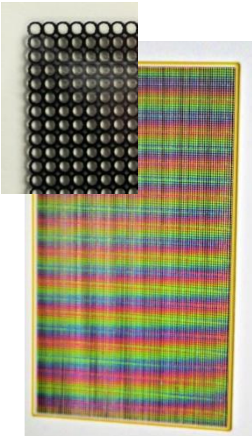
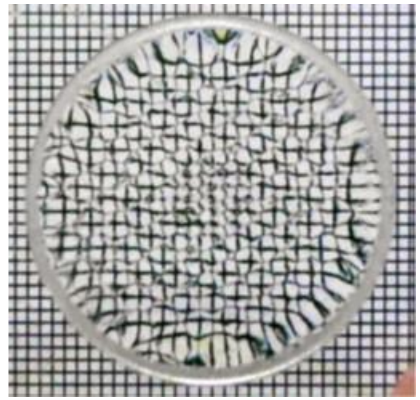
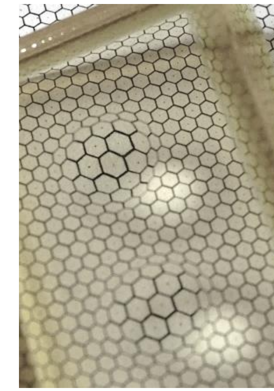


Planar Lenslet Arrays: *90 x 160, 0.75 mm baffled lens array* ***125 mm x 75 mm*** *over LCD (left) 10-mm f4 hex pack lens array (right)*



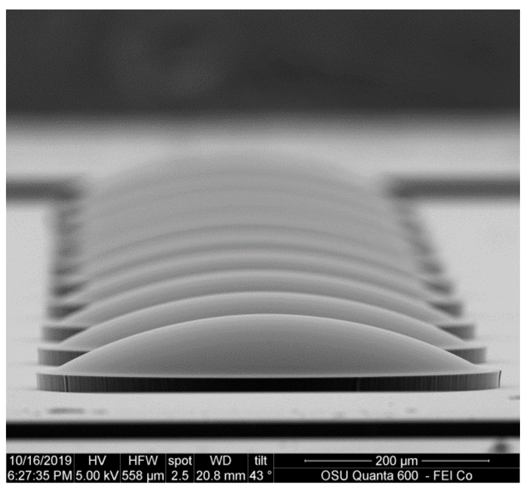
Anamorphic, chirped lenslet array

Phase corrector plates:
4” shown

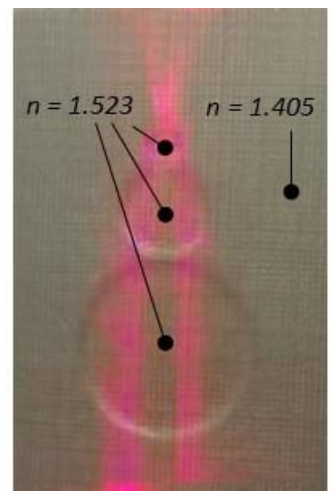


Planar 10-mm f4 *lenses over hex grid*

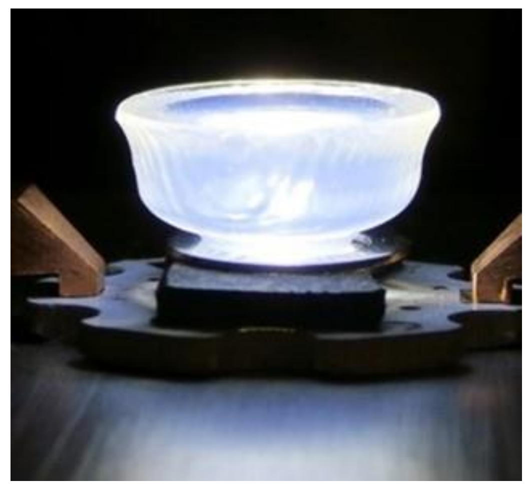
f/3 lenses*: 4 mm on 5 mm pitch (top), 0.5 mm in hex array (bottom)*



AM Convex 500 µm R65 µm *lenses, with ± 1 µm SAG*



Light steering within plane using Δn
25 x 25 mm



LED Collimator: 10 mm w.freeform surface & w/freeform GRIN

Sample VIRGO printed optical element examples

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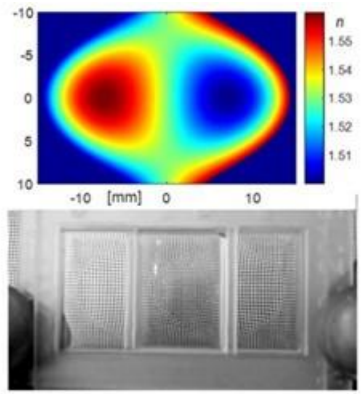
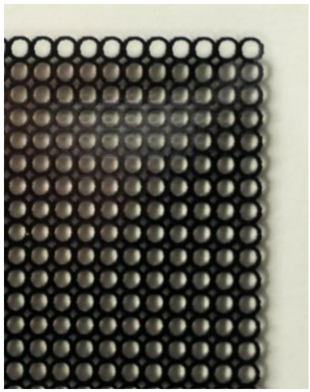
Lenslet Arrays: 160 µm aperture, 32,400 lens array (left), & 10-mm aperture *f*4 lens array (right)

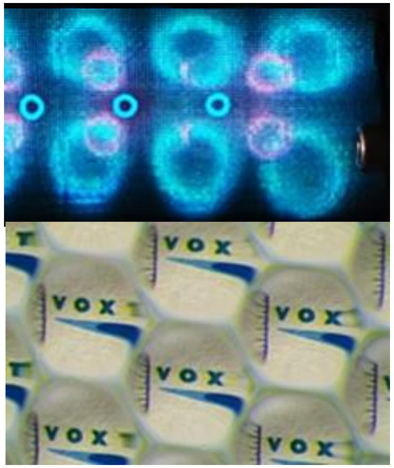


GRIN Alvarez Lens
±6 diopters

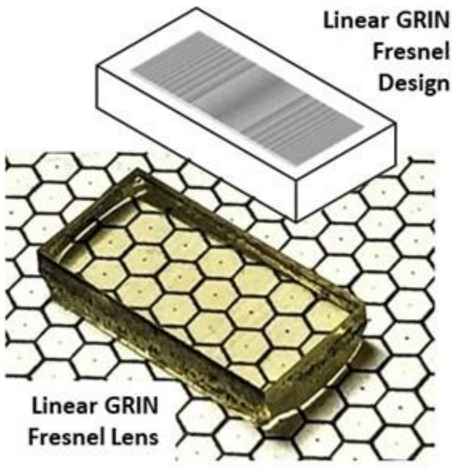
Spherical Polish:
25 mm, f3.9



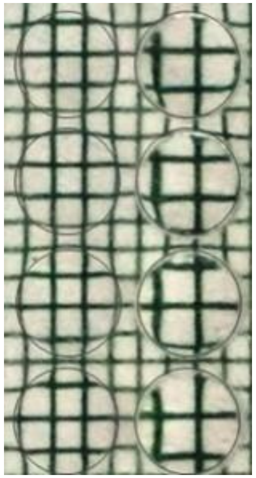
Printed Baffles and Aperture Stops



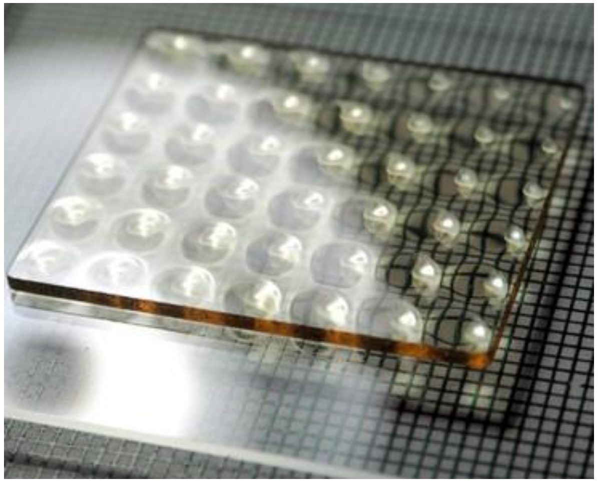
f/3 hogel lens: 125x75 mm 14.4k lens array (top), 0.5 mm in hex array (bottom)



10 mm Fresnel Barrel Lens: f2.5 uniaxial, plano-plano

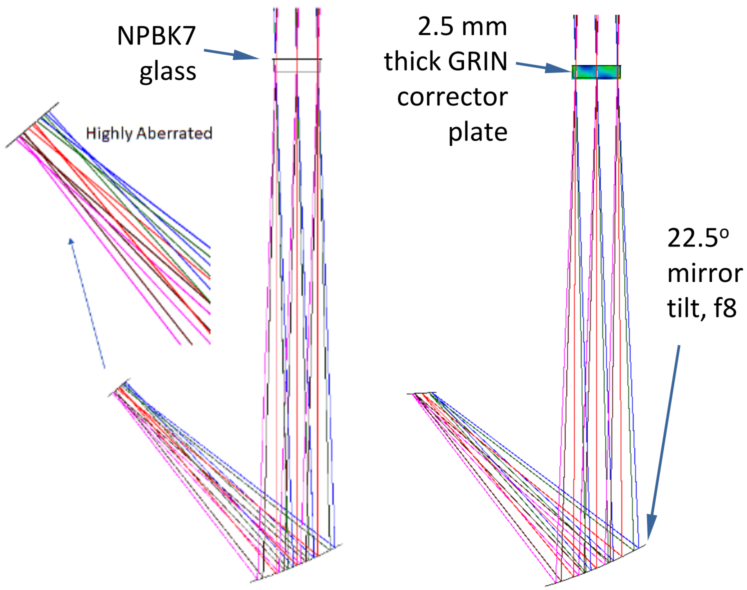


Printed Shape: 4 mm *f*4 GRIN plano (left), w/convex surface (right)



Planar Lens Arrays: 4 mm *f*4 GRIN lenses on 5 mm pitch

Completely Freeform Gradient Patterns

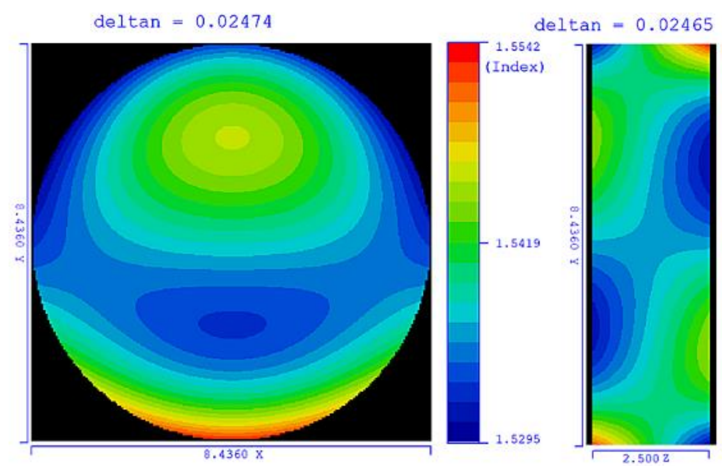


Compact NASA freeform mirror optical system for cubesats w/o (left) and w PCP

RMS Spot Dia - mm	Baseline	With VIRGO	Improved
Min	0.0186	0.0032	**6x**
Max	0.0331	0.0082	**4x**
Avg	0.0239	0.0054	**4.4x**
Std Dev	0.0036	0.0012	**3x**

Focal spot size Improvement (across FOV)

- **VIRGO phase corrector plate**
  - Provides better wavefront control across field
  - Reduced focus various across field



Phase Corrector Plate
(8.44 mm dia, 2.5 mm thick, Δn = 0.025)

The EPIC Question!!

- **What can we do for you?**

  GRIN optics design

  Printed optics

- **What can you do for Vadient?**

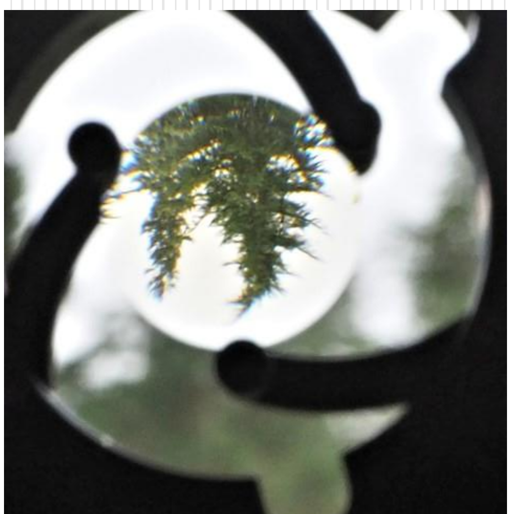
  High index polymers partners

  High volume inkjet printers

  Distribution partners/service bureau

Additively Manufactured Freeform Gradient Index Optics

Thank You!



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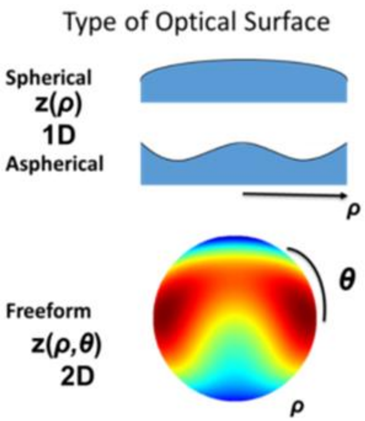
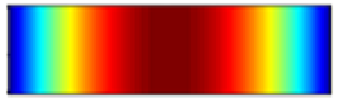
Available Classes of VIRGO Optics

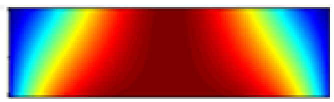


1D & 2D Homogeneous

Power and optical functions obtained from surface



Radial; n[ρ]

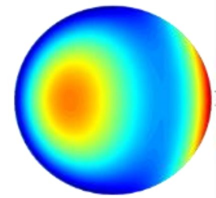


Axial and radial; $n(z_b,\rho)$]

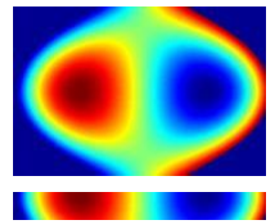
Axial and radial with printed or polished surface; $[z(\rho),(n(z_b,\rho)]$

1D, 2D & 3D Radial GRIN

Power and aberration correction by dn/dρ & $dn/d(z_b,\rho)$ with power from surface $dz_s/d\rho$



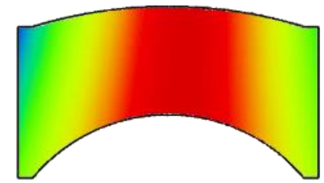
2D Freeform; $n(\rho,\theta)$]



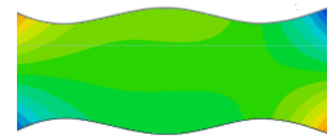
3D Freeform; $n(z_b,\rho,\theta)$]

2D & 3D Planar Freeform GRIN

non symmetric, higher order polynomial functions



(A)spheric Surface w. freeform Grin; $[z(\rho), n(z_g,\rho,\theta)]$



Freeform surface w. freeform GRIN; $[z(\rho,\theta),n(z_g,\rho,\theta)]$

4D & 5D Surfaced Freeform GRIN

Machined, polished, or printed freeform surface and freeform GRIN

- **Radial and Freeform GRIN increases design degrees of freedom (dof)**
  - **Chromatic correction additional dof**
- **3D GRIN structure easily defined with polynomials (Zernike, etc)**
- **Can be modeled using custom plug-ins for Zemax and CodeV**